NASA JSC Lunar Surface Concept Study
Lunar Energy Storage

NNJ08TA84C
U.S. Chamber of Commerce Programmatic Workshop

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Agenda

- Scope/Objectives
- Trade Study Requirements, Trade Space and Figures-of-Merit
- Task I: Trade Results, Literature Search Results
- Task I: Proposed Power Beaming Concept Feasibility
- Task I: Proposed Power Beaming Technology Development
- Task II: Other Lunar Energy Storage Technologies for Comparison
- Conclusions
- Recommended Future Work

Scope

- **There are two major tasks:**
  - Evaluate the power beaming technologies at an appropriate orbit and spacecraft constellation to provide lunar night power
  - Provide a comparison of power beaming design with other surface energy storage technologies for lunar night power needs

Trade Study Requirements, Trade Space and Figures-of-Merit

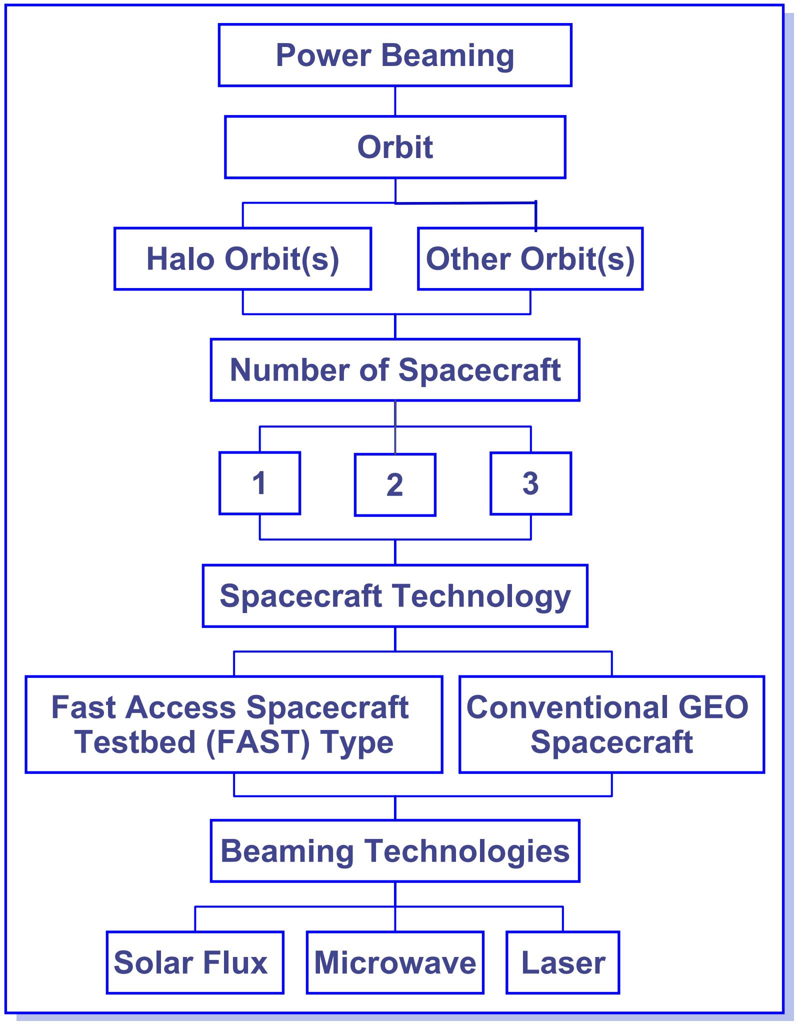
Requirements (per Broad Agency Announcement NNJ08ZBT002)

- 2 - 5 kW_e surface electrical power (user)
- 100 – 2,000 kW-hr net energy storage per module
- TRL 6 by 2015 - 2018 timeframe
- 5 - 10 year calendar life
- 10,000 - 15,000 hour operational life
- 100 – 2,000 charge/discharge cycles
- Ability to withstand high dust, radiation, and widely varying thermal environment
- Anywhere location on lunar surface

Lunar Surface Energy Storage Assessment Process

Task 1: Power Beaming for Lunar Night Power Needs

- **Requirements**
- **FOM assumptions**
- **Literature search**
- **Orbital models**
  - AGI STK/Astrogator



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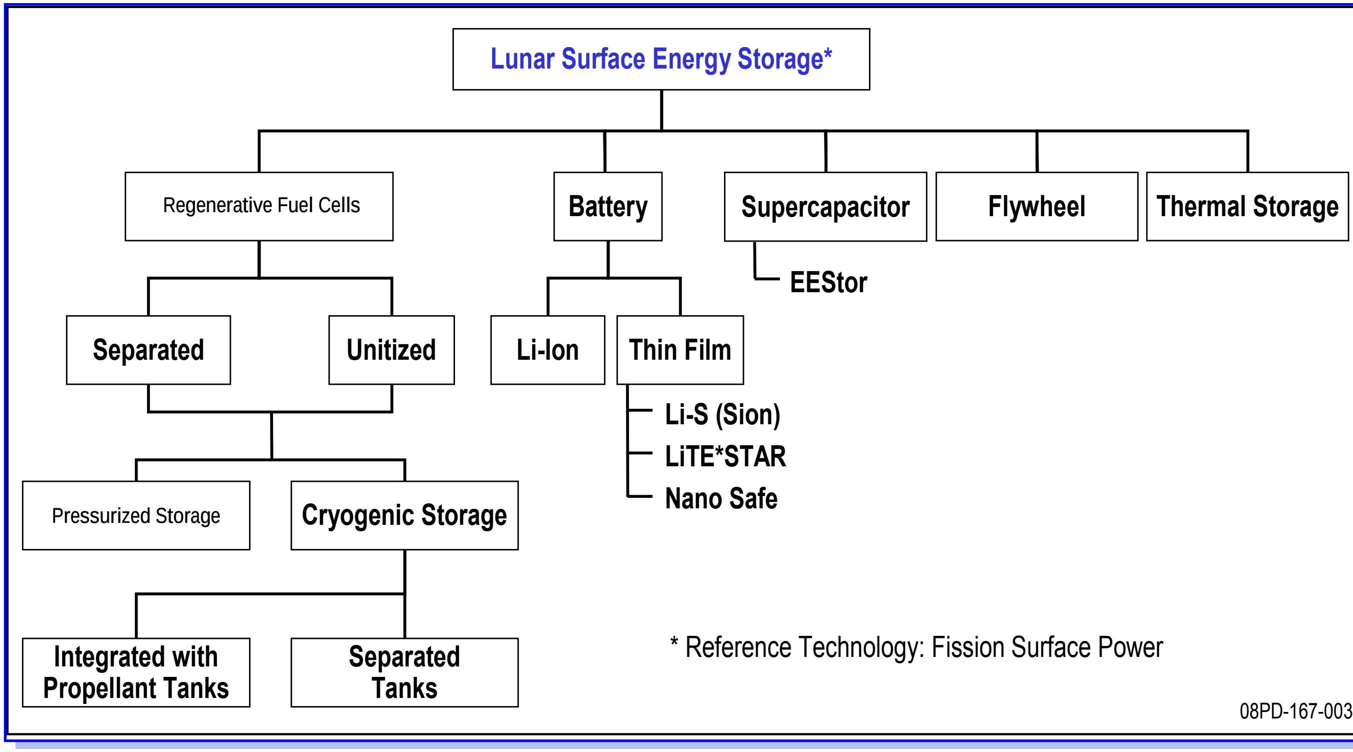
Lunar Surface Energy Storage Assessment Process

Task 2: Comparison of Lunar Energy Storage Options

- **Requirements**
- **FOM assumptions**
- **Literature search**
- **Technology evaluation**



Figures-of-Merit

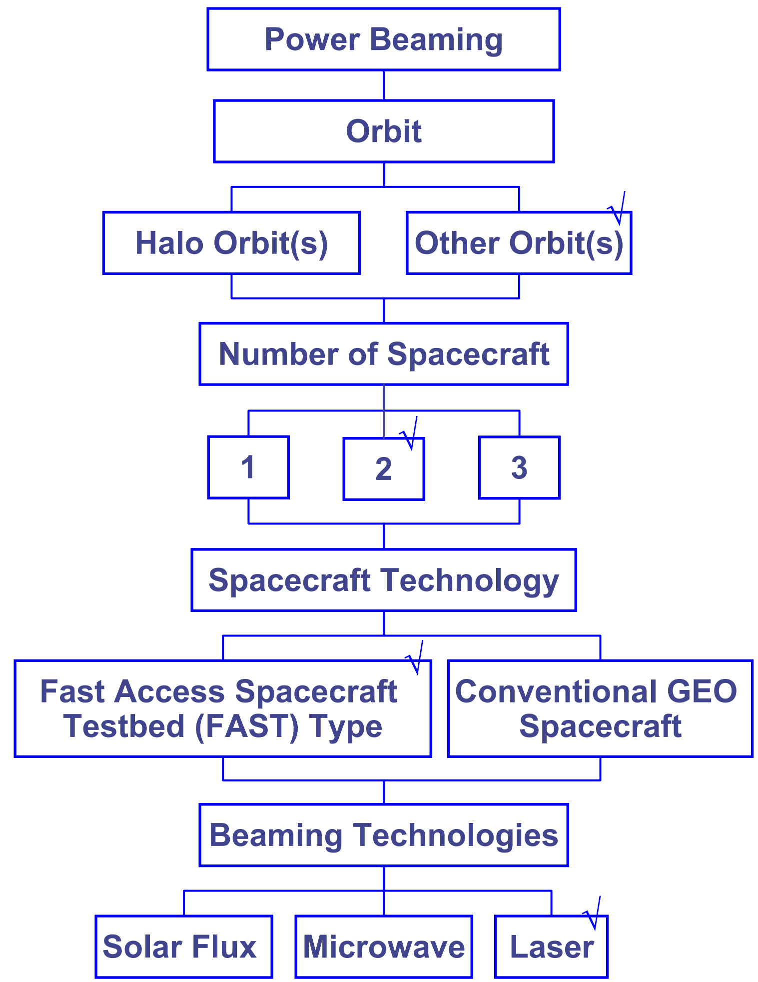
- **Quantitative FOM's**
  - Mass
  - Launch Volume
  - System Efficiency
  - Technical Readiness Level (TRL)

- **Qualitative FOM's**
  - Operational Effectiveness: Integration, Redundancy, Mobility, …
  - Development Schedule
  - Relative Cost

Task I Trade Study

Task 1 Conclusions

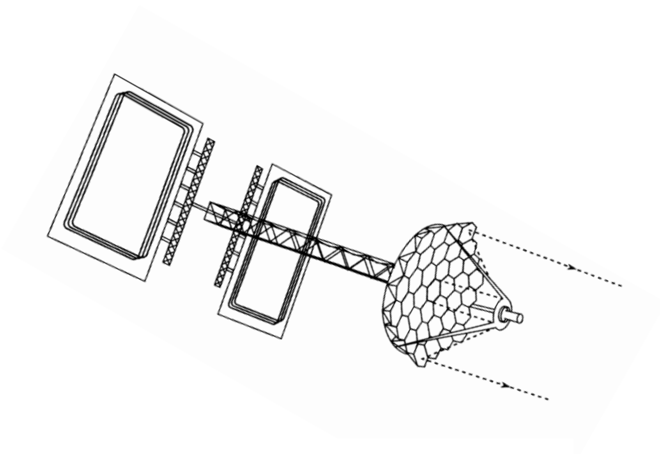
- **A frozen lunar orbit (16.1 hr period) appears promising**
  - Provides a reasonable gap time and maximum range
    - 10,731 km maximum range (2020)
    - 14 hour gap time (Jan to Dec 2020)
    - 15.6 hour gap time with pointing error & elevation angle constraints
- **One spacecraft provides a good trade-off between cost/mass & coverage**
  - Two spacecraft provide redundancy
- **FAST spacecraft provides lower mass and related transportation cost**
- **Laser power beaming technology provides smallest surface footprint.**



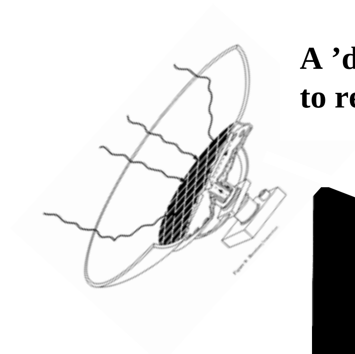
Configurations have ability to integrate telecommunications function with power infrastructure

Literature Search Results
NASA Langley Research Center Report*

“ This study addresses the possibility of beaming laser power from synchronous lunar orbits…. to a manned long-range lunar rover. “



On-orbit PV power laser beaming power to lunar rover



A ’dish-like” laser receiver mounted on lunar rover to receive and convert laser power to electric power

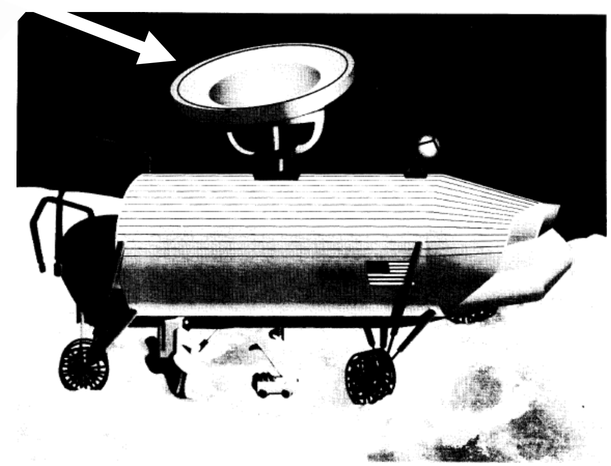


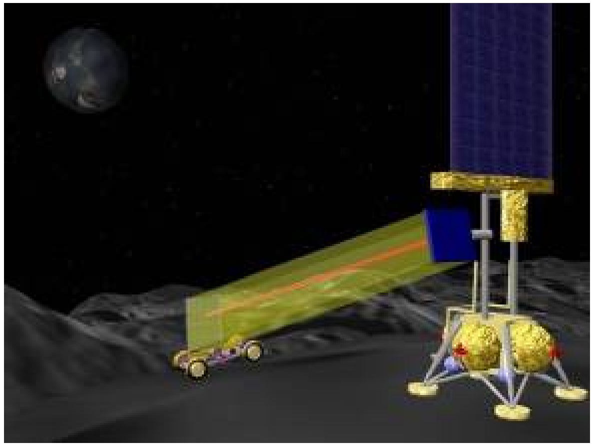
Figure 7. Lunar rover.

- **Small receiver diameter and large laser beam (aperture) diameter due to long distance power transmission**

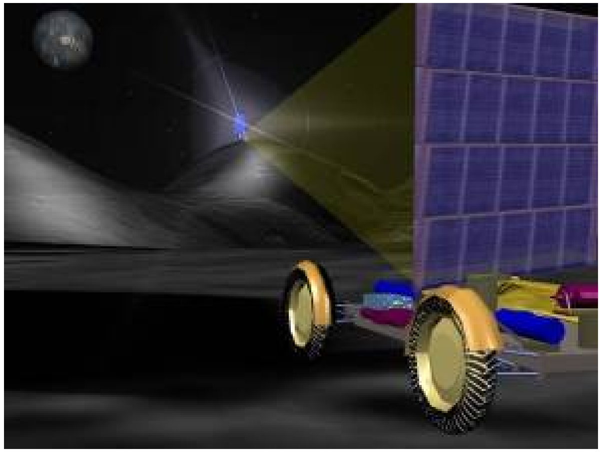
* Williams, M.D., DeYoung, R.J., Schuster, G.L., and Choi H.S., “Power Transmission by Laser Beam from Lunar-Synchronous Satellite,” NASA TM-4496, November 1993.

Literature Search Results
NASA Glenn Research Center Report*

"A human lunar outpost, … has potential requirements to transfer electric power up to 50-kW across the lunar surface from 0.1 to 10-km distances..“



Lunar Lander sending laser power beam to rover



Rover receiving laser power beam from Lunar Lander

- **Trades among AC or DC power via cables, beamed radio frequency power and beamed laser power**
- **Small receiver and beam aperture diameters due to short distance**

* Kerslake, Thomas W., "Lunar Surface-to-Surface Power Transfer," NASA/TM-2007-215041, NASA Glenn Research Center, December 2007

Groundrules and Assumptions

- **Space Element**
  - 130 W/kg specific power for electrical power system (FAST)
    - Employs CPV cell technology
  - Fixed spacecraft bus and propulsion system dry mass
    - 200 kg and 30 kg, respectively
  - Yearly station-keeping ΔV budgets
    - 132 m/s for L_1 and L_2 halo orbits
    - 22.9 m/s for lunar polar, equatorial and 45° inclination orbits
  - Laser module and dc-to-dc converter unit (DDCU) power electronics
    - Combined 50% efficiency and 50 W/kg composite specific power based on
      - 830 nm laser wavelength
      - Laser diode module and DDCU power electronics specific mass
        - 12 kg/kW and 6.3 kg/kW, respectively
        - 10 percent additional mass allocation for structure and integration
  - 2 kg/m^2 laser module heat rejection radiator areal density
  - 1,367 W/m^2 solar insolation

Ground Rules and Assumptions – Concluded

- **Surface Element**
  - Laser receiver employs thin-film (CIGS) photovoltaic technology
    - 50 % combined efficiency, 10 year life
      - Based 830 nm wavelength (~ 0.7 transmission efficiency x 0.8 quantum efficiency)
    - 1367 W/kg specific power
      - Based on 0.5 kg/m^2 areal density and 50% efficiency
  - Required infrastructure to maintain dust-free surface is not included

Functional Block Diagram and Energy Balance

Power Beaming Architecture Space Power Element

Solar Power Collection & Concentration → Solar Power Conversion → 10, 14 & 22 kW_e power generation → Elec. Power Conversion → Laser Conversion

Solar Power Collection & Concentration	Solar Power Conversion		Elec. Power Conversion	Laser Conversion
70%*	30%	10, 14 & 22 kW_e power generation	95% (DDCU)	~50% (Laser)

* Function/ Assembly Efficiency

Power Beaming Architecture Surface Power Element

Laser Power Transmission/ Collection → Laser Power Conversion → Elec. Power Conversion → 2, 3 & 5 kW_e to user at night

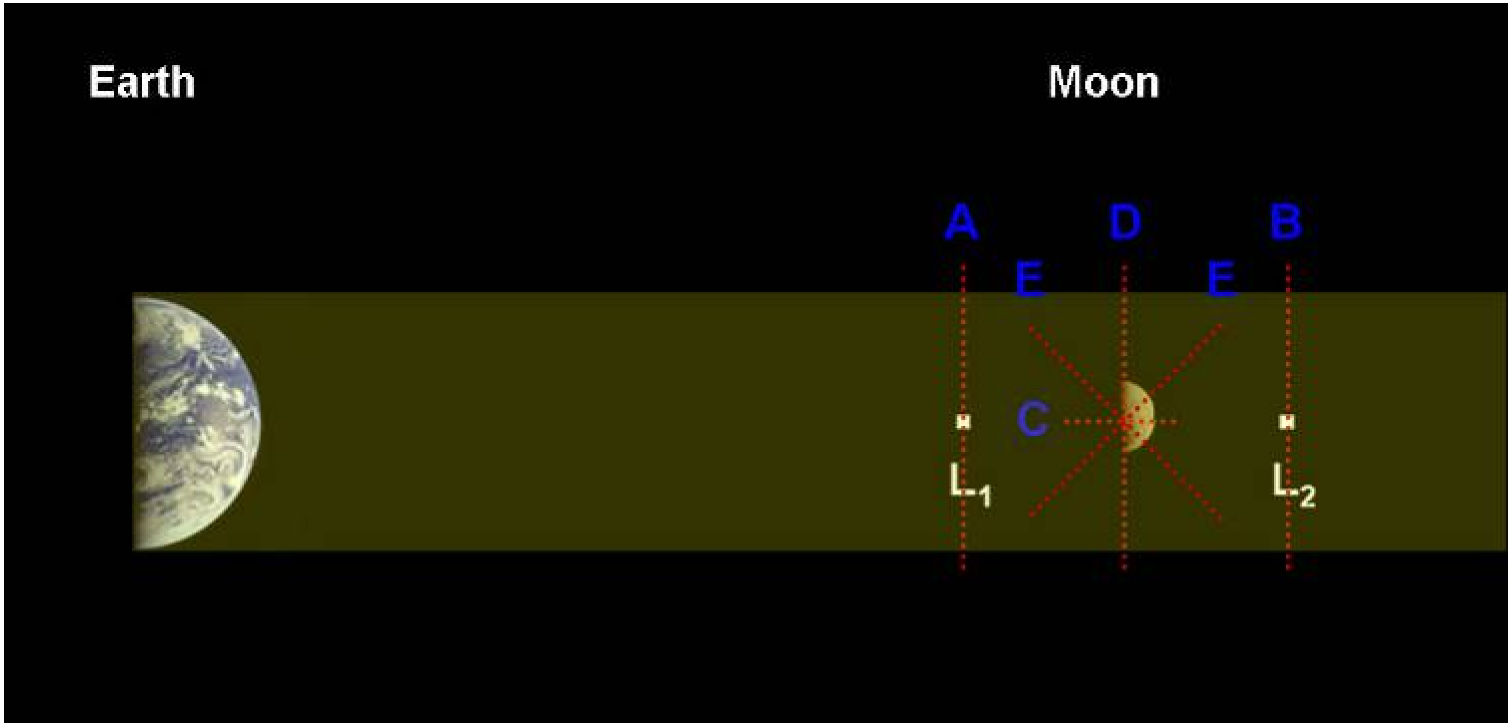
Laser Power Transmission/ Collection	Laser Power Conversion	Elec. Power Conversion	
60 - 70%	80%	95% (DDCU)	2, 3 & 5 kW_e to user at night

Energy Storage Architecture Surface Power Only Element

Solar Power Conversion → 800, 1200 & 2000 kW_e-hr energy → Energy Storage → Elec. Power Conversion → 2, 3 & 5 kW_e to user at night

Solar Power Conversion		Energy Storage	Elec. Power Conversion	
< 20% (CIGS) / 28% (5J)	800, 1200 & 2000 kW_e-hr energy	95% (Li-Ion Battery)	95% (DDCU)	2, 3 & 5 kW_e to user at night

Round 1: Candidate Solar Power Collection Spacecraft Orbits



Note: not to scale.

A. Earth-Moon libration point L_1 circular halo orbit (1 spacecraft)
B. Earth-Moon libration point L_2 circular halo orbit (1 spacecraft)
C. Lunar circular equatorial orbit (1 spacecraft)
D. Lunar circular polar orbit (1 spacecraft)
E. Lunar elliptical orbit, 45° inclination, 1 to 2 planes (1 spacecraft per plane)

Round 1 Candidate Orbit Definitions

- **Earth-Moon libration point L_1 halo orbit (1 spacecraft)**
  - 3,700 km halo radius, near stationary with respect to lunar surface, 58,000 km distance, multiple halo orbit inclination options
- **Earth-Moon libration point L_2 halo orbit (1 spacecraft)**
  - 3,700 km halo radius, near stationary with respect to lunar surface, 64,500 km distance, multiple halo orbit inclination options
- **Lunar equatorial orbit (1 spacecraft)**
  - 36 hour orbit period, 11,039 km / 0° inclination
- **Lunar polar orbit (1 spacecraft)**
  - 36 hour orbit period, 11,041 km / 0° inclination
- **Lunar frozen orbit, 45° inclination, 1 plane (1 spacecraft)**
  - 36 hour orbit period, 5,928 x 16,149 km
- **Lunar frozen orbit, 45° inclination, 2 planes (1 spacecraft per plane)**
  - 36 hour orbit period, periapsis points clocked 180 degrees apart

Candidate Orbit Comparison Summary

Candidate Orbit	Advantages	Disadvantages
Earth-Moon libration point L_1 circular halo orbit (1 spacecraft)	Almost always in sunlight Simpler pointing & tracking Flexible surface sites (front side)	**Large surface footprint (119 m)** **Heavy surface receiver (27X)** **Much costly (> 10X)** Station-keeping propellant (6X)
Earth-Moon libration point L_2 circular halo orbit (1 spacecraft)	Almost always in sunlight Simpler pointing & tracking Flexible surface sites (far side)	**Large surface footprint (132 m)** **Heavy surface receiver (33X)** **Much costly (> 12X)** Station-keeping propellant (6X)
Lunar circular equatorial orbit (1 spacecraft constellation)	**Small surface footprint (23 m)** Minimal shadow time Minimal station-keeping prop.	Pointing & tracking complexity Limited to equatorial sites
Lunar circular polar orbit (1 spacecraft constellation)	**Small surface footprint (23 m)** Minimal shadow time Minimal station-keeping prop.	Pointing & tracking complexity Limited to single long. sites
Lunar elliptical orbit, 45 deg inclination, 1 to 2 planes (1 to 2 spacecraft constellation)	**Small surface footprint (34 m)** Minimal station-keeping prop. Flexible surface sites	Pointing & tracking complexity 2X cost over single spacecraft

L1 or L2 Halo orbit is not appropriate candidate for lunar surface power beaming

Spacecraft Technology Comparison

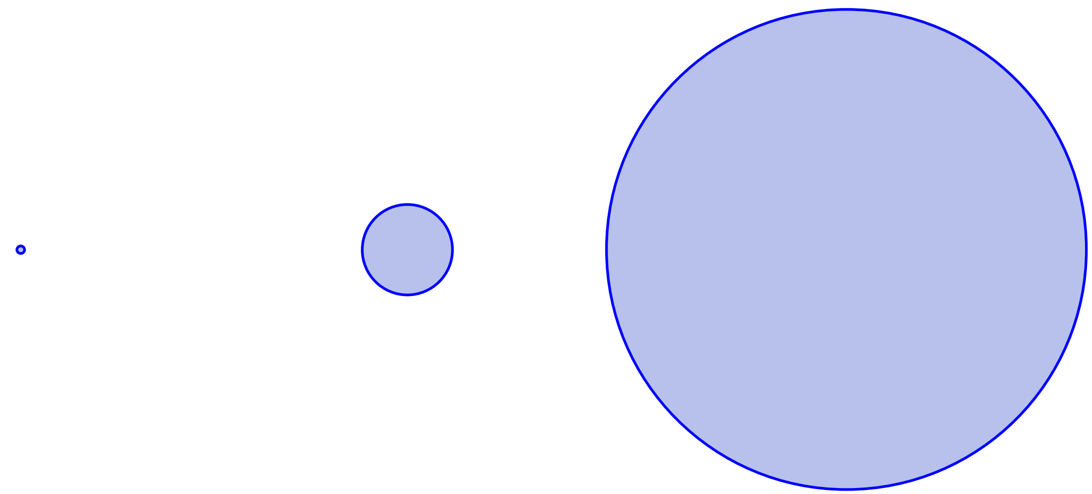
	FAST	Conventional S/C
Specific Power of S/C (W/kg)	40	< 4
Specific Power of Electric Power System (W/kg)*	130	< 55

* Solar power collection, power conversion, electrical power management and distribution systems, heat rejection and all supporting structures, including pointing and deployment mechanisms along with sun pointing and tracking mechanisms

FAST spacecraft with electric propulsion is a feasible candidate for lunar mission

Beaming Technology Trade - Footprint Comparison

	Laser	**Solar Flux**	**Microwave**
Wavelength (μm)	0.830	10.075	53.534 (5.6 GHz)
Beam diameter (m)	1.0	1.0	1.0
Distance (km)	10,731	10,731	10,731
Receiver diameter (m)	22.7	264.8	1,402.7
Receiver area (m^2)	**406**	**55,071**	**1,545,357**



Laser-PV is the choice for lunar surface power beaming technology

Task I Trade Study Round 2 Additional Gs&As

- **10° latitude, -45° longitude surface site**
- **Mission time of 2020**
- **0.05° laser beam pointing error**
- **Min. of 30° elevation angle constraint (trade study results)**
- **Energy storage architecture**
  - **200W-hr/kg energy storage technology**
  - **95% charge/discharge (roundtrip) cycle efficiency**
- **Frozen orbit(s) trade among 8 to 48 hour circular/elliptical orbits**
  - **Result: Near-optimal elliptical orbit, 45° inclination, 16.1 hr orbit period**
    - max. of 14 hour gap time without elevation angle constraint for year of 2020
      - 10,731 km maximum range
    - max. of 15.6 hour gap time with minimum 30° elevation angle & year of 2020
      - 9,977 km maximum range

- **"Gap" time is defined as the time when spacecraft is not providing power to the surface site during lunar night**
  - **S/c and surface site line-of-sight is not available or not practical or**
  - **S/c is not in direct sunlight**
  - **Surface energy storage would be required during gap time**

Power Beaming Energy Balance with Gap Time

Power Beaming Architecture Space Power Element

Solar Power Collection & Concentration → **Solar Power Conversion** → **27 kW$_e$ power generation** → **Elec. Power Conversion** → **Laser Conversion**

70%* | 30% | 95% (DDCU) | ~50% (Laser)

* Function/Assembly Efficiency

Power Beaming Architecture Surface Power Element

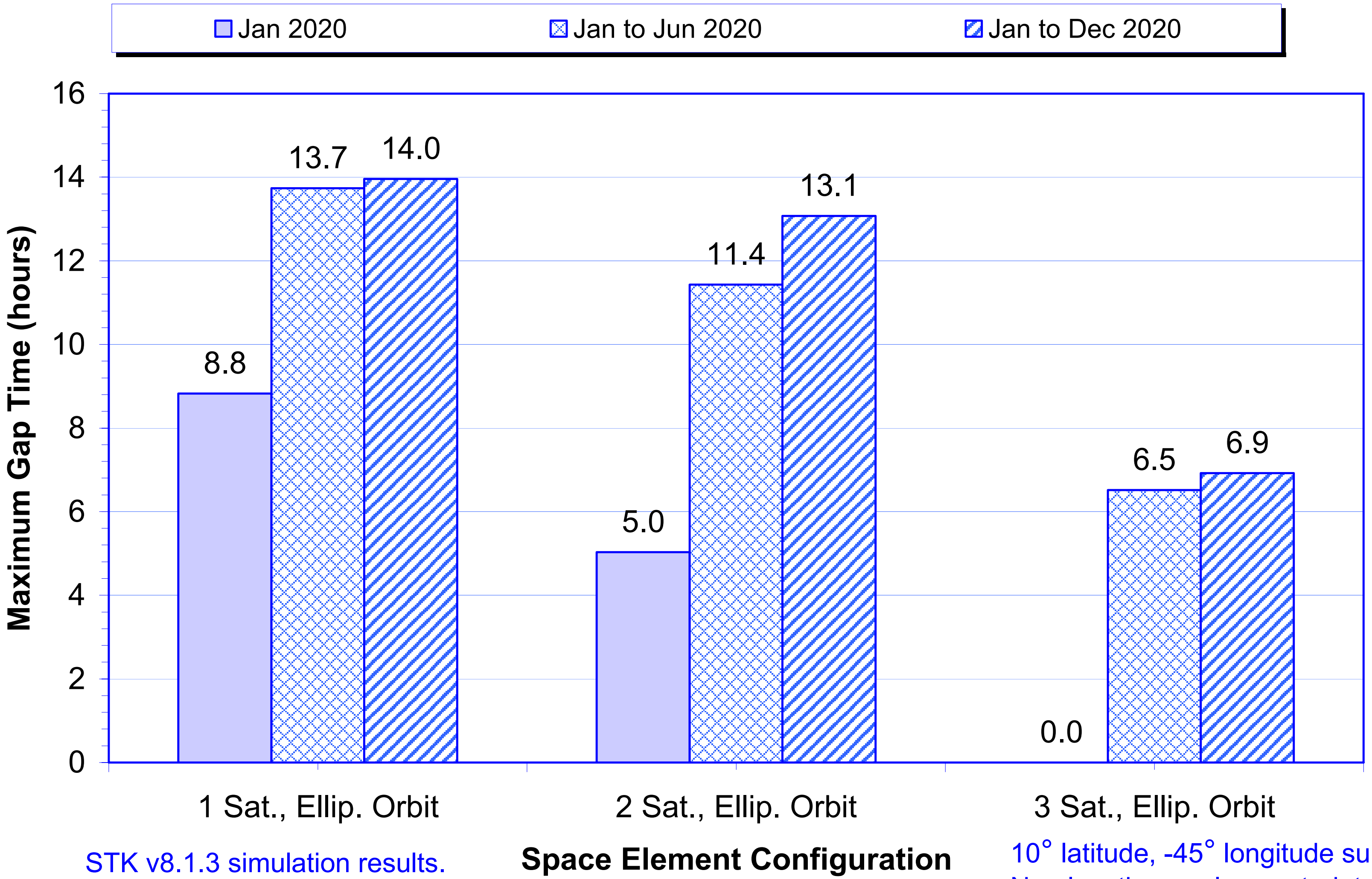
Laser Power Transmission /Collection → **Laser Power Conversion** → **Elec. Power Conversion** → **5 kW$_e$ to user**

60 - 70% | 80% | 95% (DDCU)

525 kW-hr ⇅ **Energy Storage**

95% (Li-Ion Battery)

Max. Gap Summary – 16.1 Hour Orbit Period



STK v8.1.3 simulation results.

10° latitude, -45° longitude surface site
No elevation angle constraints

Mission time and duration and # of s/c's drive Gap time

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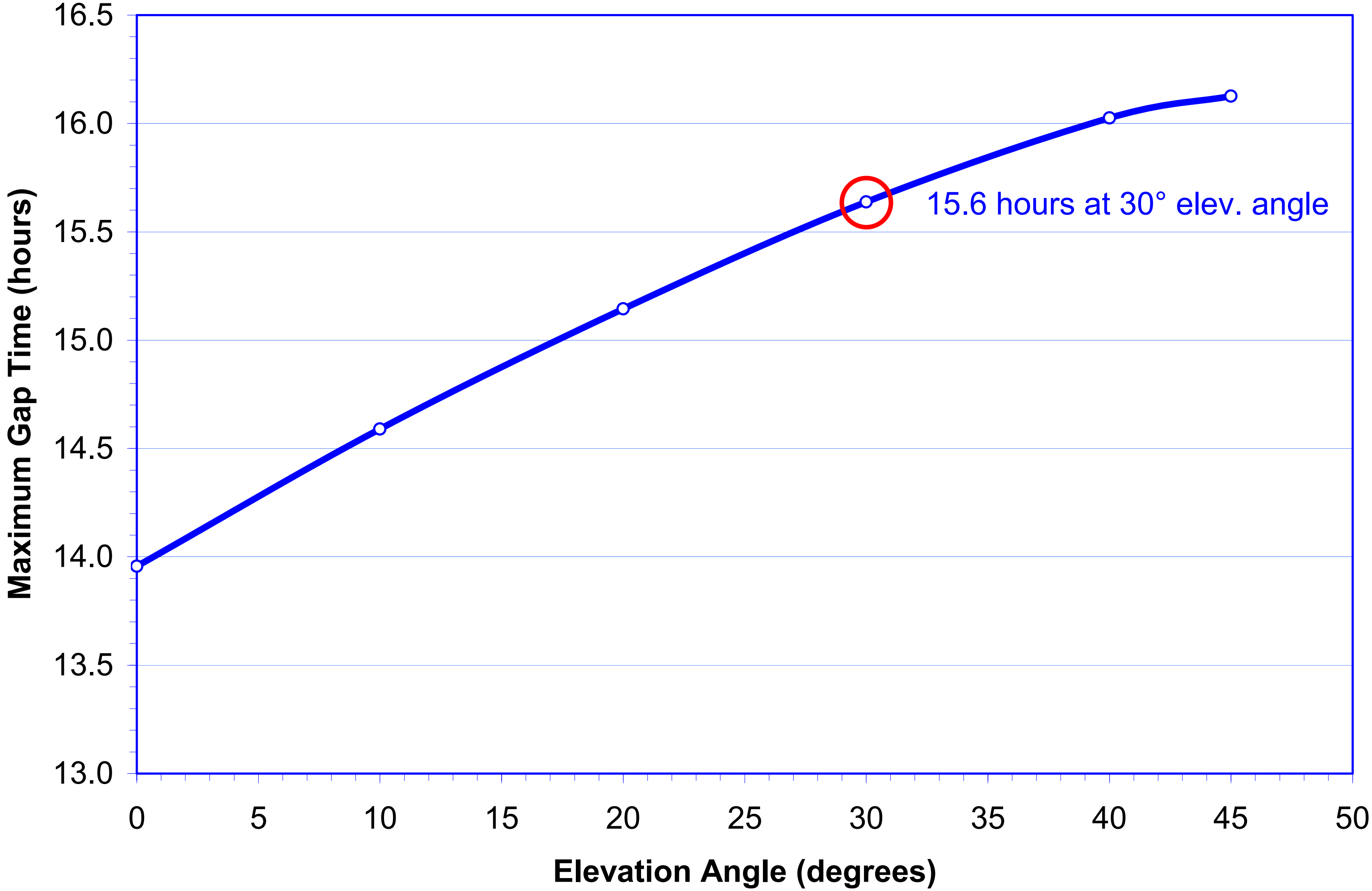
Max. Gap Time Versus Elevation Angle Constraint



Elliptical orbit, 45° inclination, 16.1 hour orbit period.

10° latitude, -45° longitude surface site.

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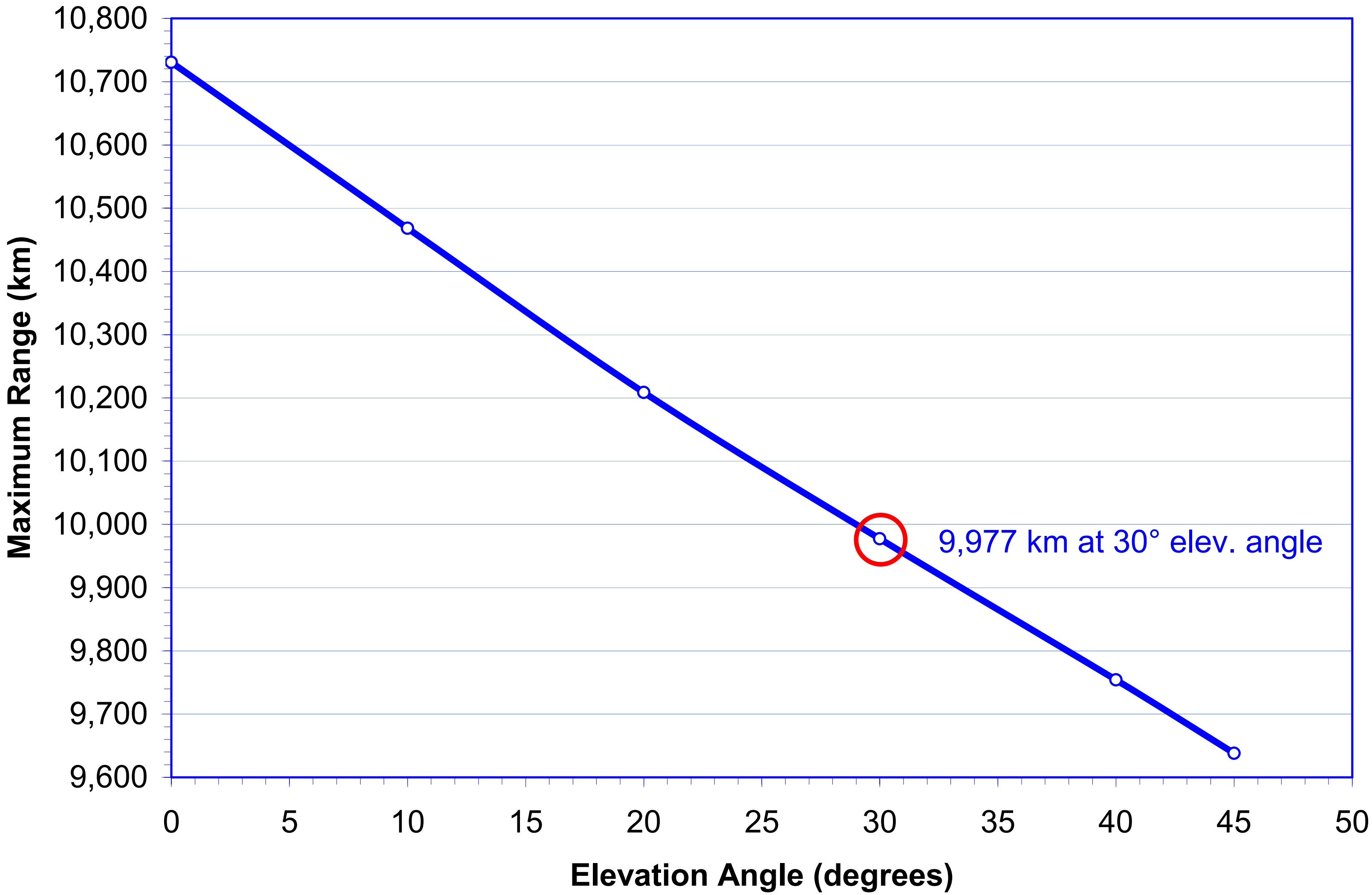
Max. Range Versus Elevation Angle Constraint



Elliptical orbit, 45° inclination, 16.1 hour orbit period.

10° latitude, -45° longitude surface site.

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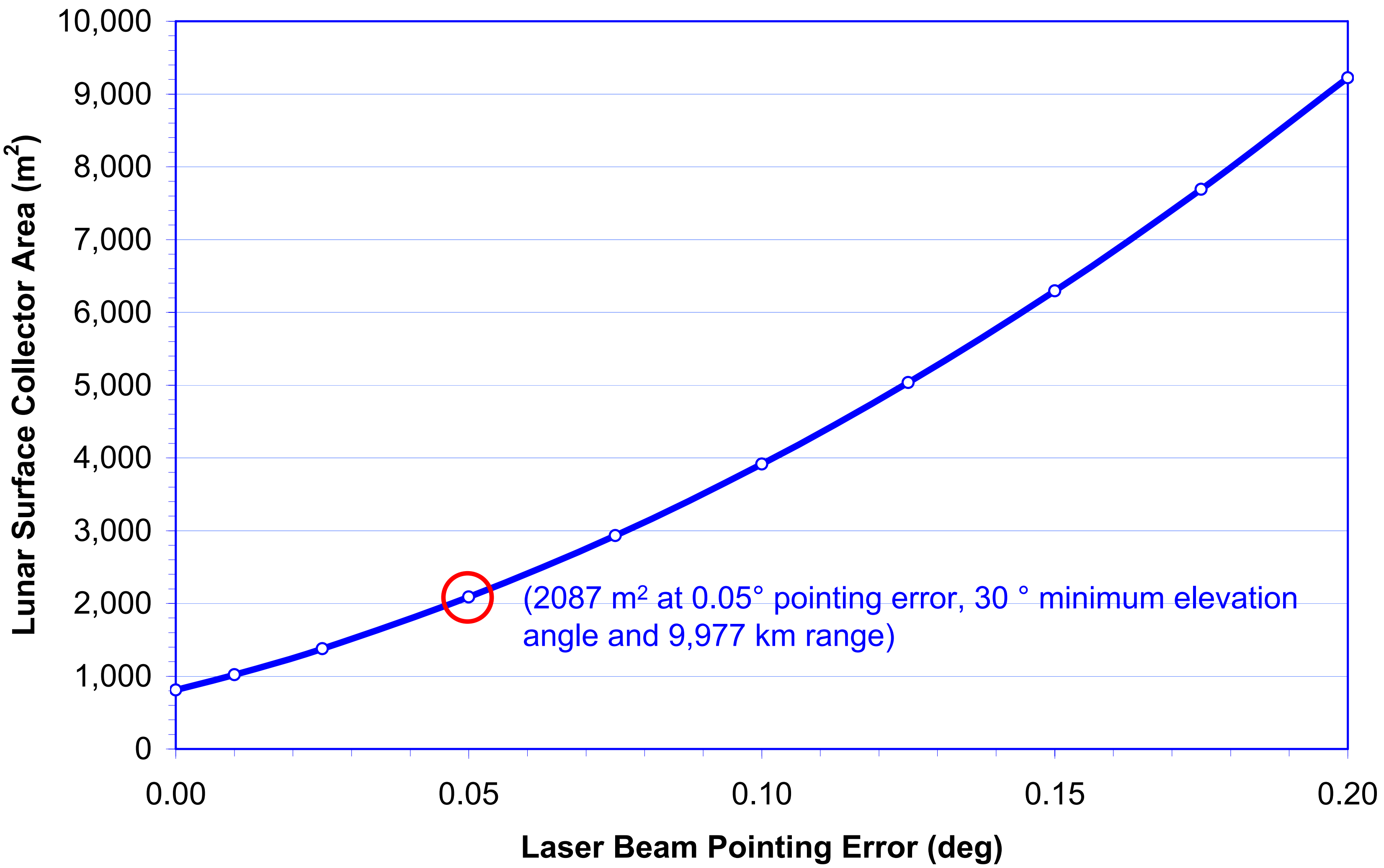
Receiver Area Variation with Pointing Error



Elliptical orbit, 45° inclination, 16.1 hour orbit period.

10° latitude, -45° longitude surface site.

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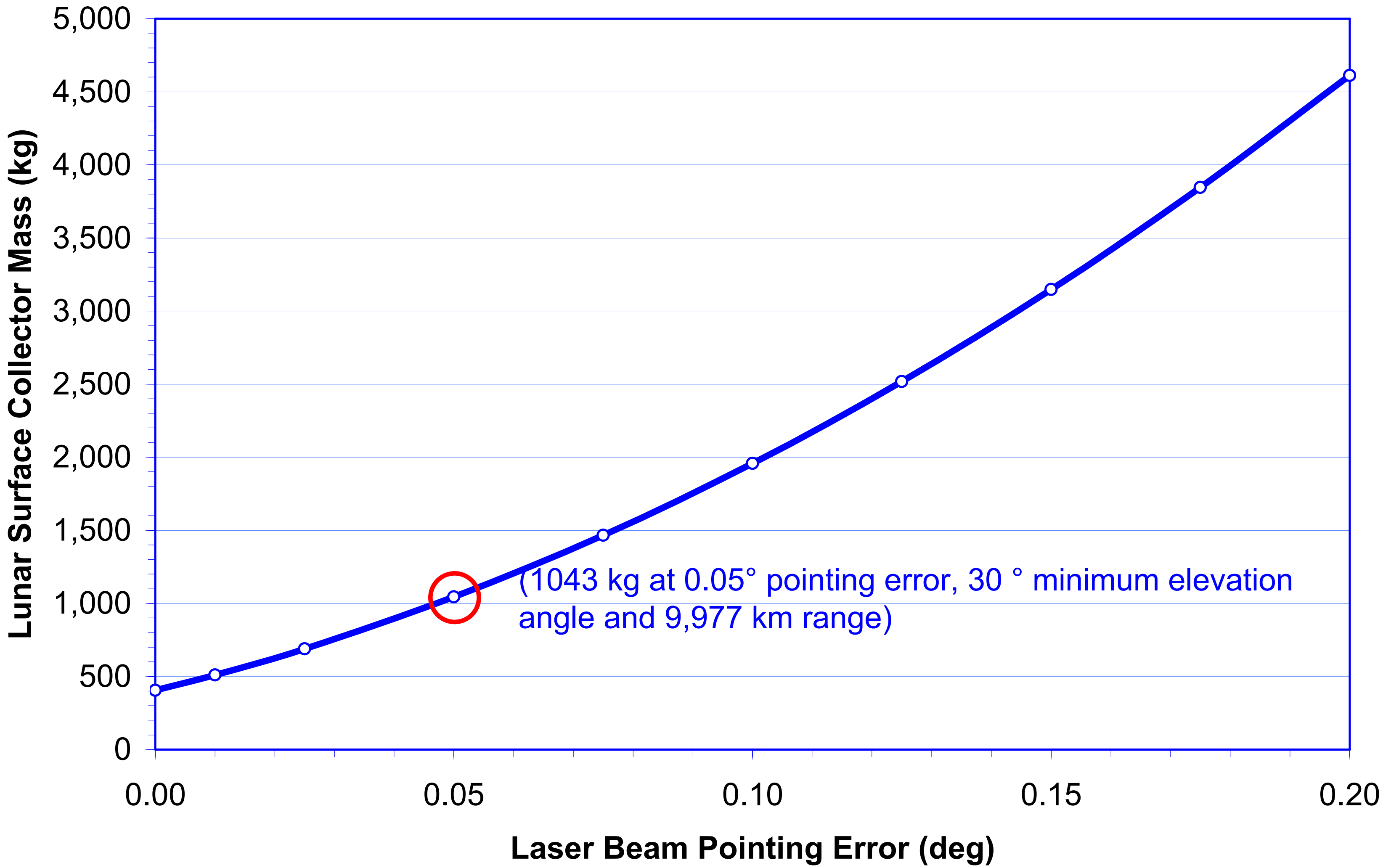
Receiver Mass Variation with Pointing Error

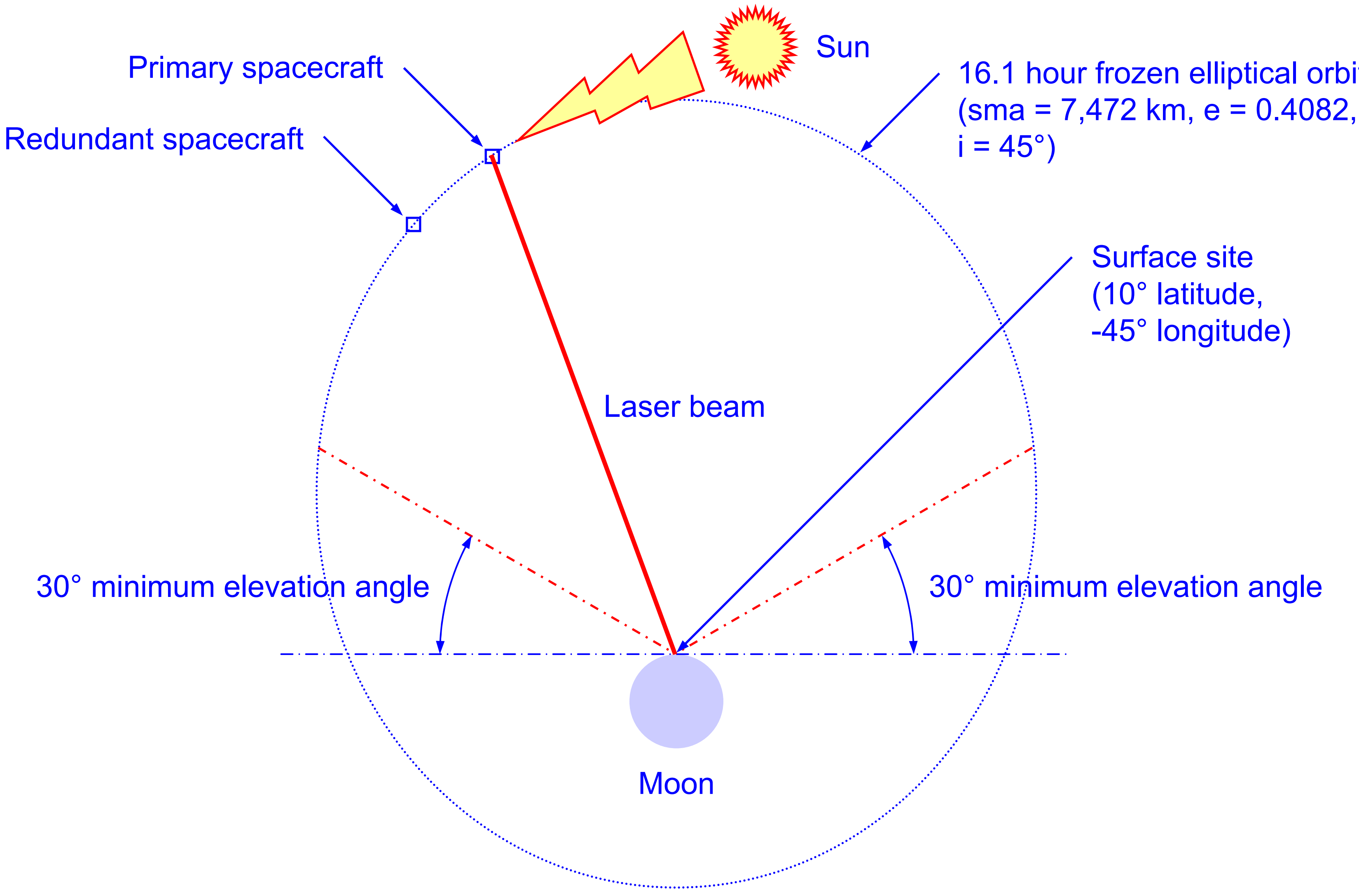


Elliptical orbit, 45° inclination, 16.1 hour orbit period.

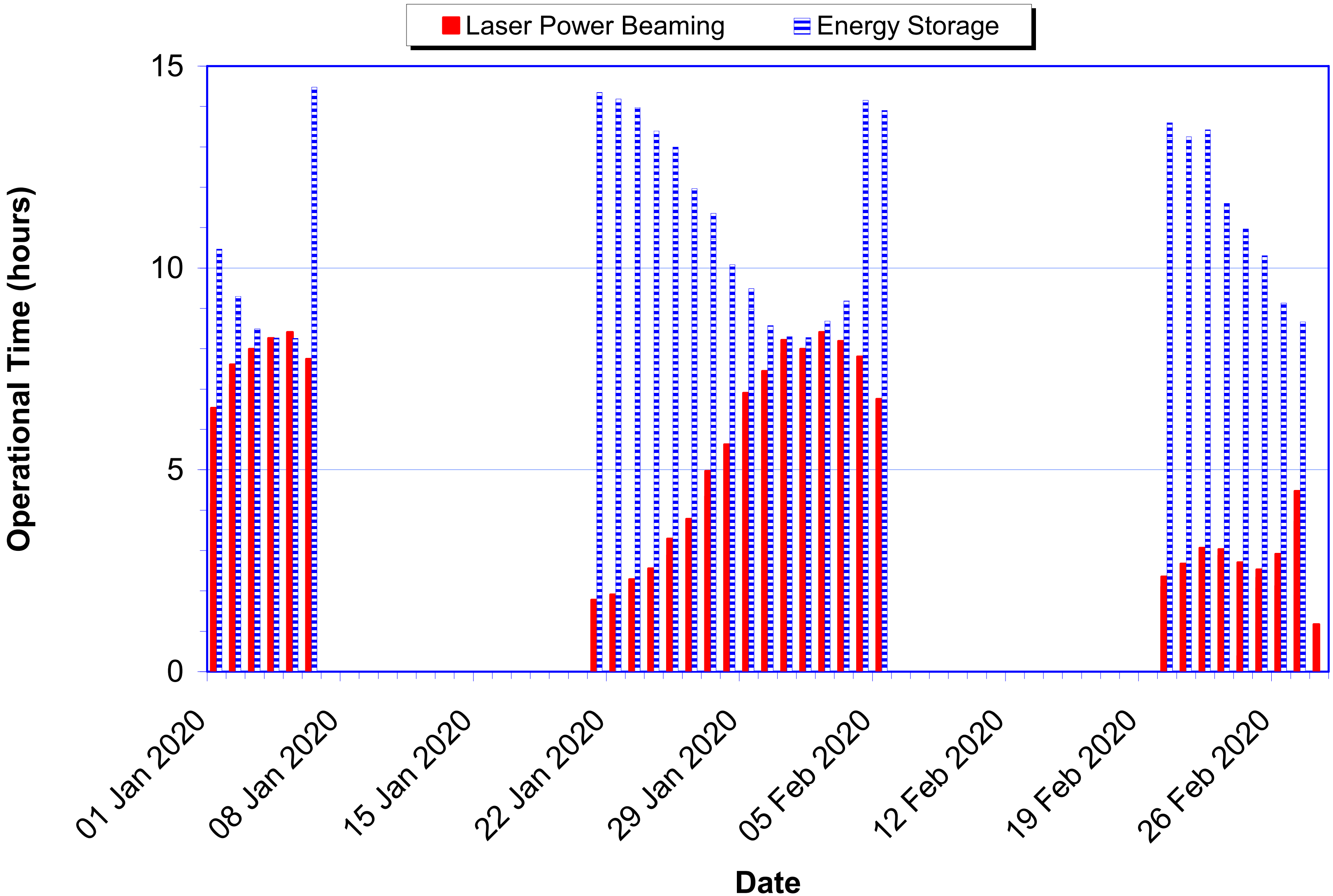
10° latitude, -45° longitude surface site.

Proposed Power Beaming Concept Feasibility

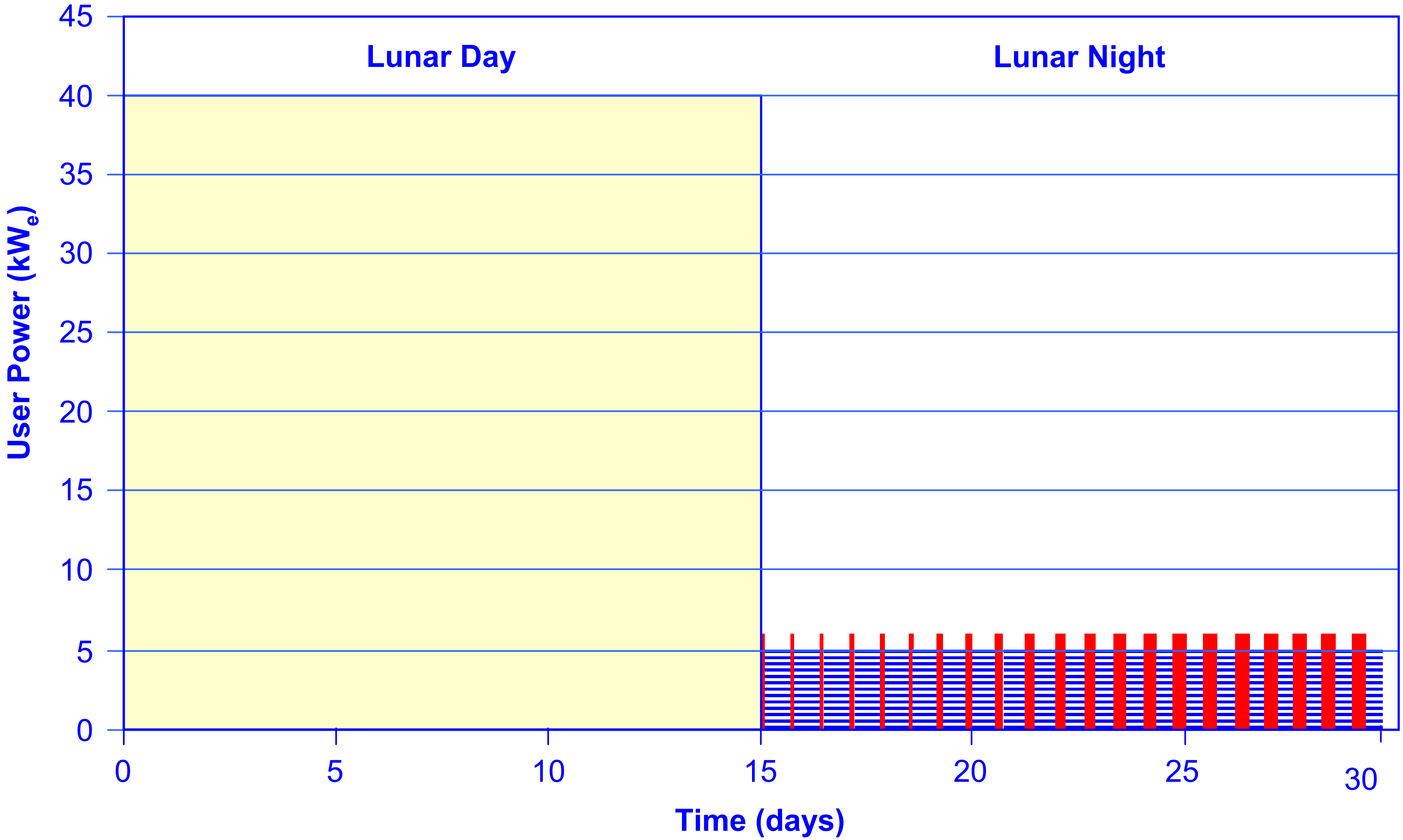
Laser Power Beaming Architecture Concept



Access and Gaps Summary – Jan through Feb 2020



Lunar Surface User Power Schedule



- Laser on (provides user power and to charge energy storage subsystem)
- Laser off (user power provided by energy storage subsystem)

Laser Power Beaming Architecture Description

- **Space Element**
  - – 3-axis stabilized spacecraft (one primary and one redundant)
  - – Electric propulsion for orbit and station-keeping operations
    - Orbit clean-up following insertion and for de-saturating CMG's
  - – Solid state laser diode technology (830 nm wavelength)
    - 1 m laser beam diameter at source
    - Two-axis tracking gimbal with a pointing accuracy of 0.05°
- **Surface Element**
  - – "Plug and play" CIGS photovoltaic array technology
  - – 16 lightweight flexible panels (receiver) with "tent" structures at each end
    - Manual deployment facilitated by two crew members
    - Minimal surface pre-treatment and minimal surface support equipment
      - – Removal of large rocks
      - – Simple alignment using known spacecraft ground track and surface position data

STK Generated 3-D Orbit Track

Elliptical orbit, 45° inclination, 16.1 hour orbit period.

10° latitude, -45° longitude surface site.

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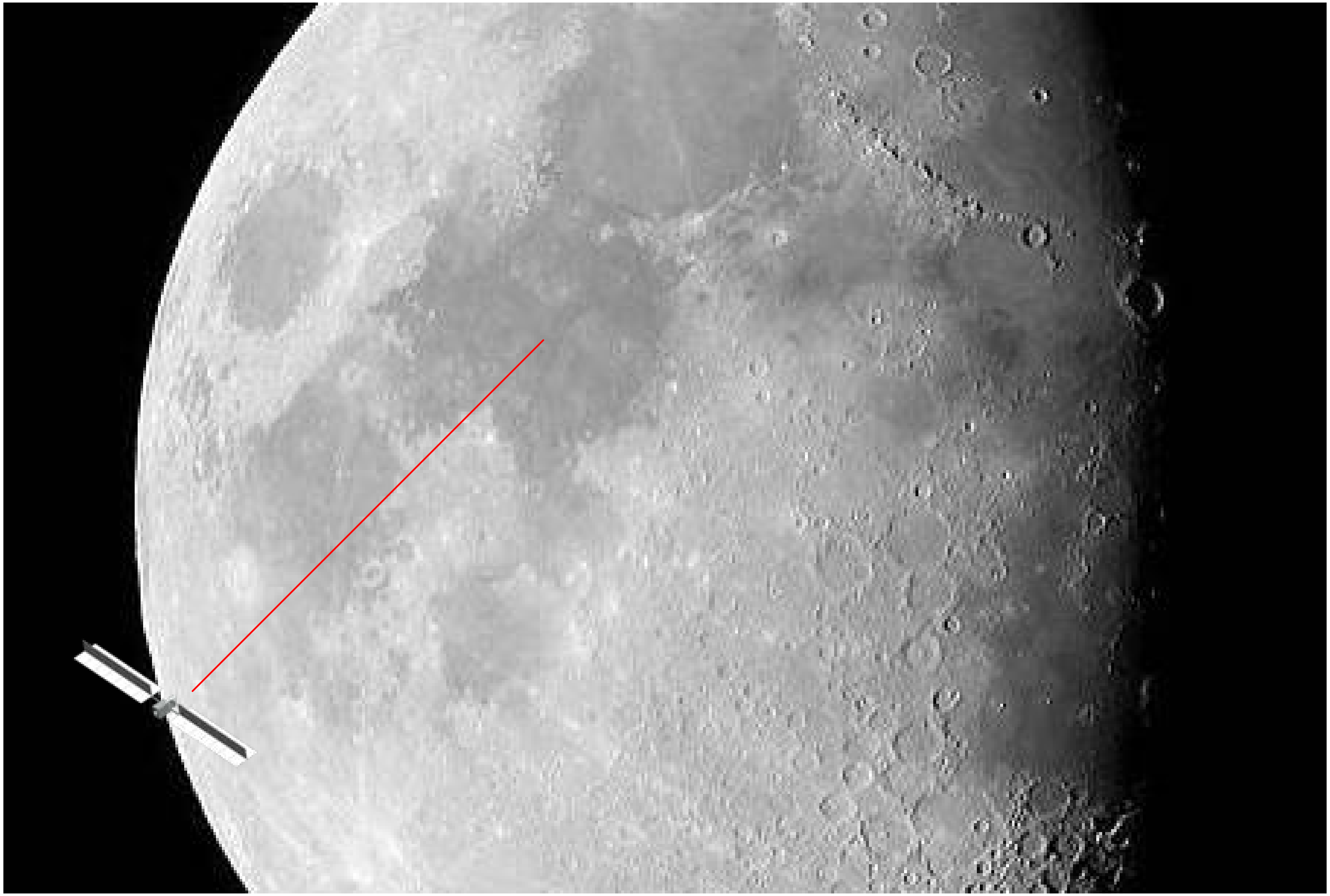
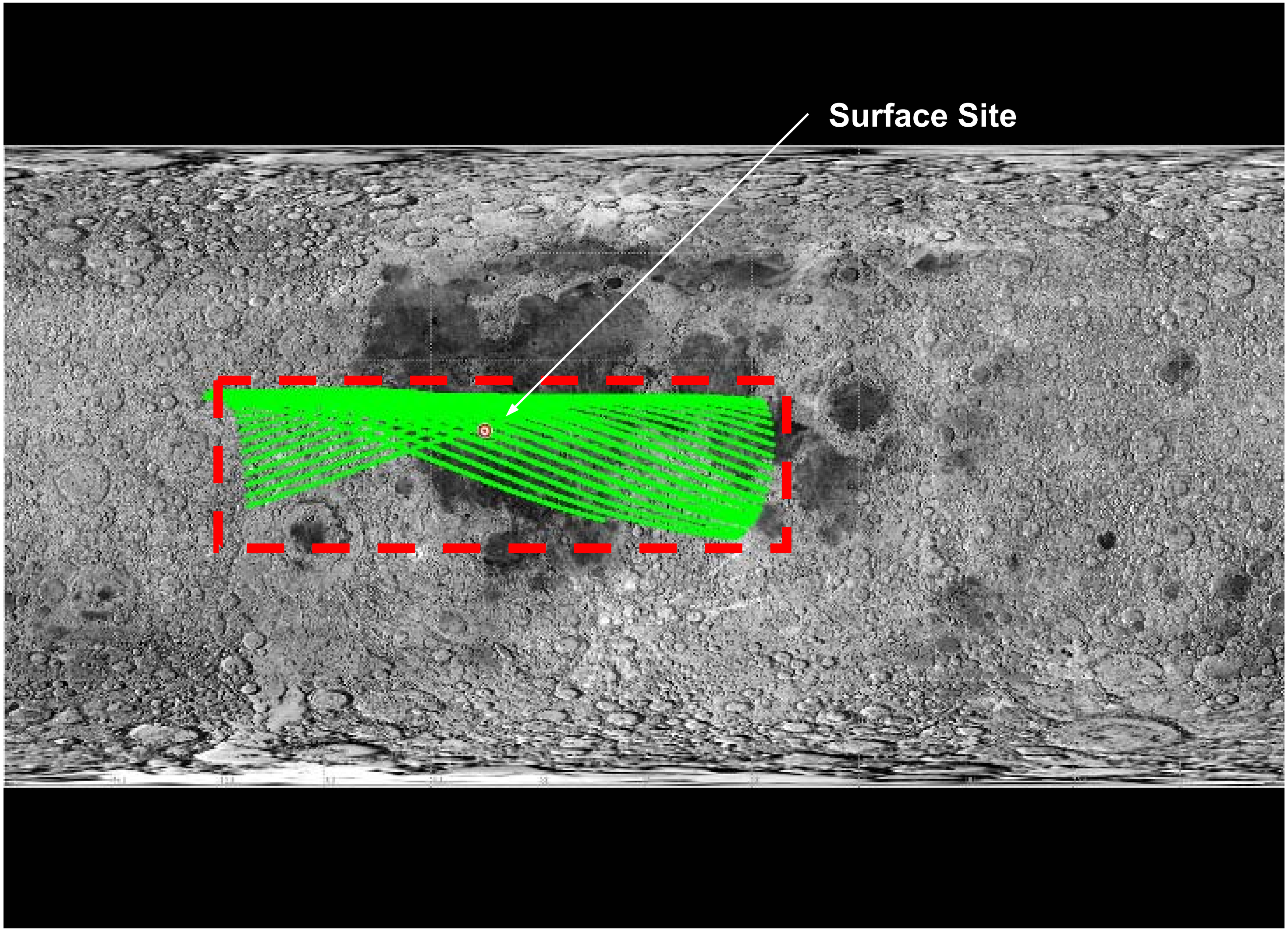
FAST Application: Power Beaming for Lunar Surface Power



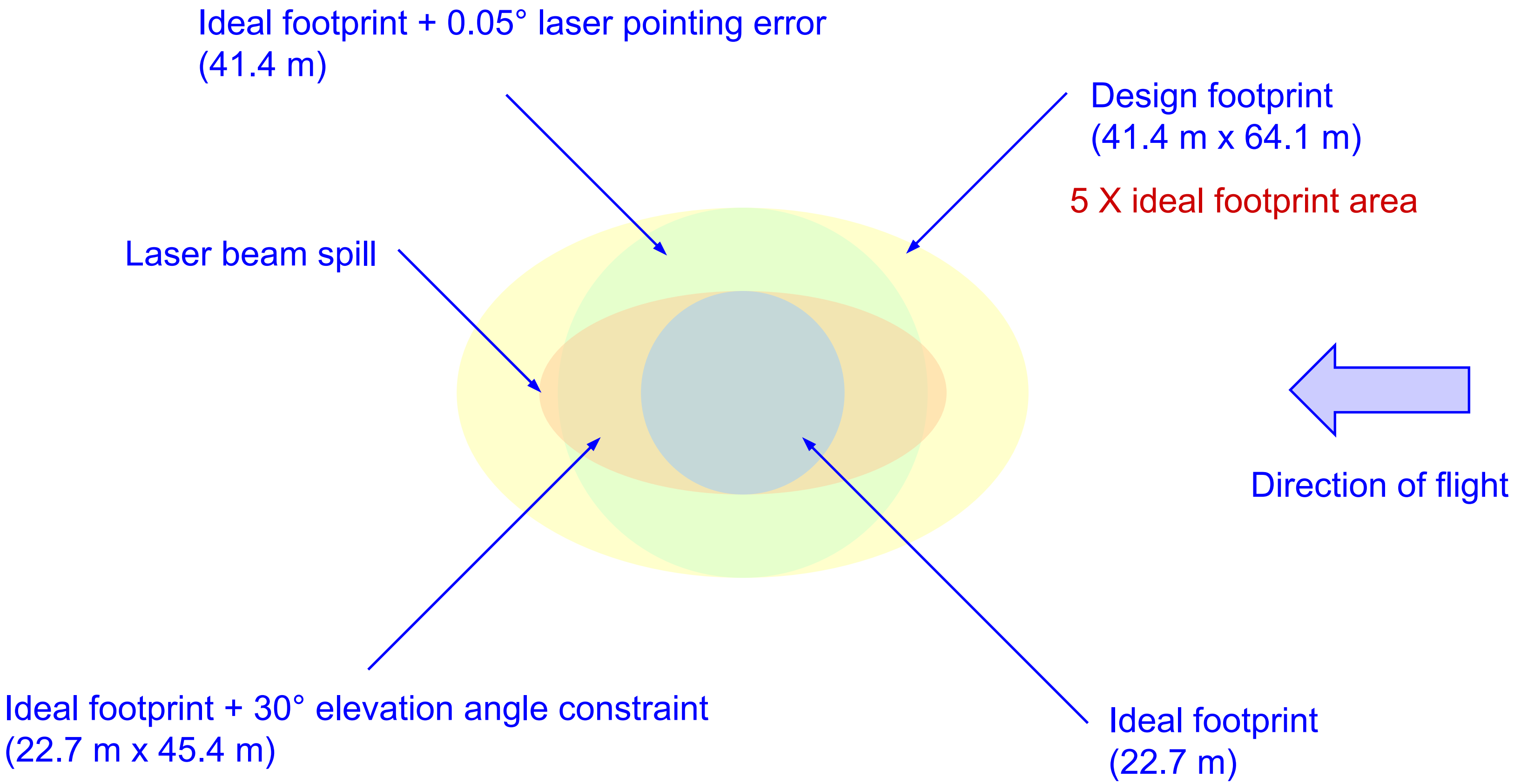
STK Generated Ground Track



Elliptical orbit, 45° inclination, 16.1 hour orbit period.

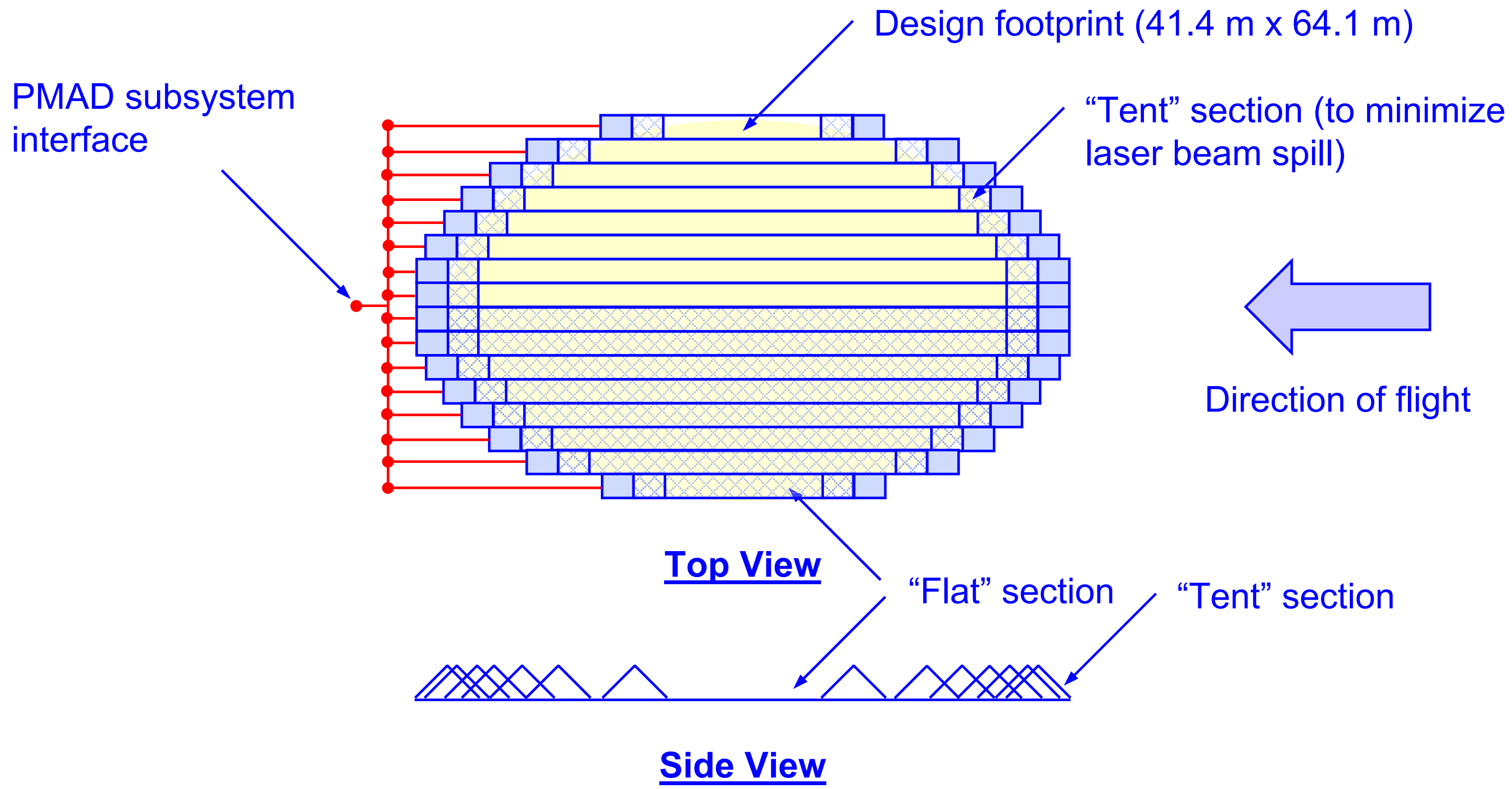
10° latitude, -45° longitude surface site.

Lunar Surface Receiver



Design footprint accounts for 0.05° pointing error and 30° minimum elevation angle constraint

Lunar Surface Receiver – 30° Min. Elevation Angle



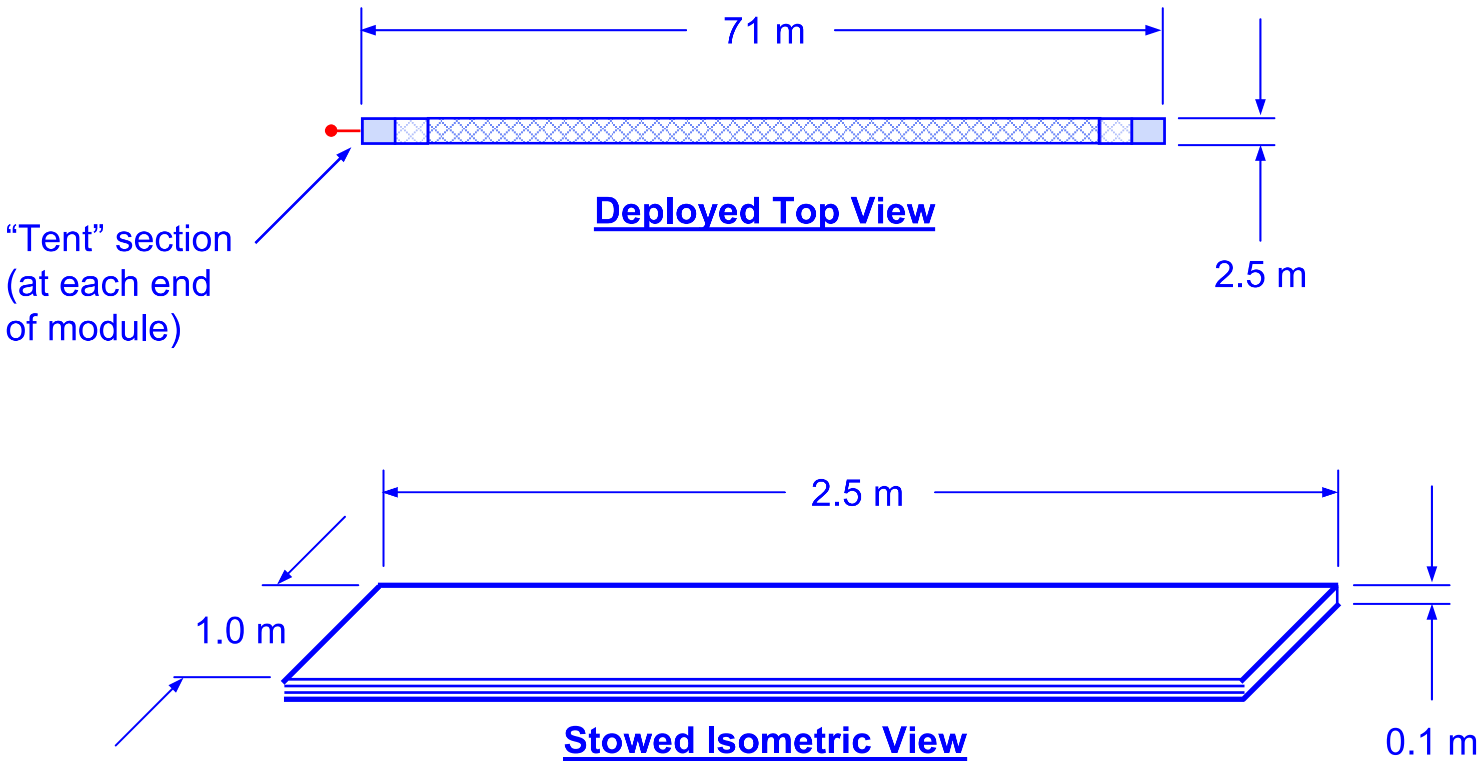
16 flexible CIGS photovoltaic array modules are complemented by "tent" structures (2.5 m wide and x 70.9 m maximum length module).

“Tent”

- **Orient the last 5 m of each end of the active photovoltaic array module to an angle of 45° to form a “tent”**

- **The “tent” structure serves two purposes**
  – Minimize laser beam spill
  – Minimize contamination of the surface receiver when surface activities are conducted in the vicinity of the surface receiver

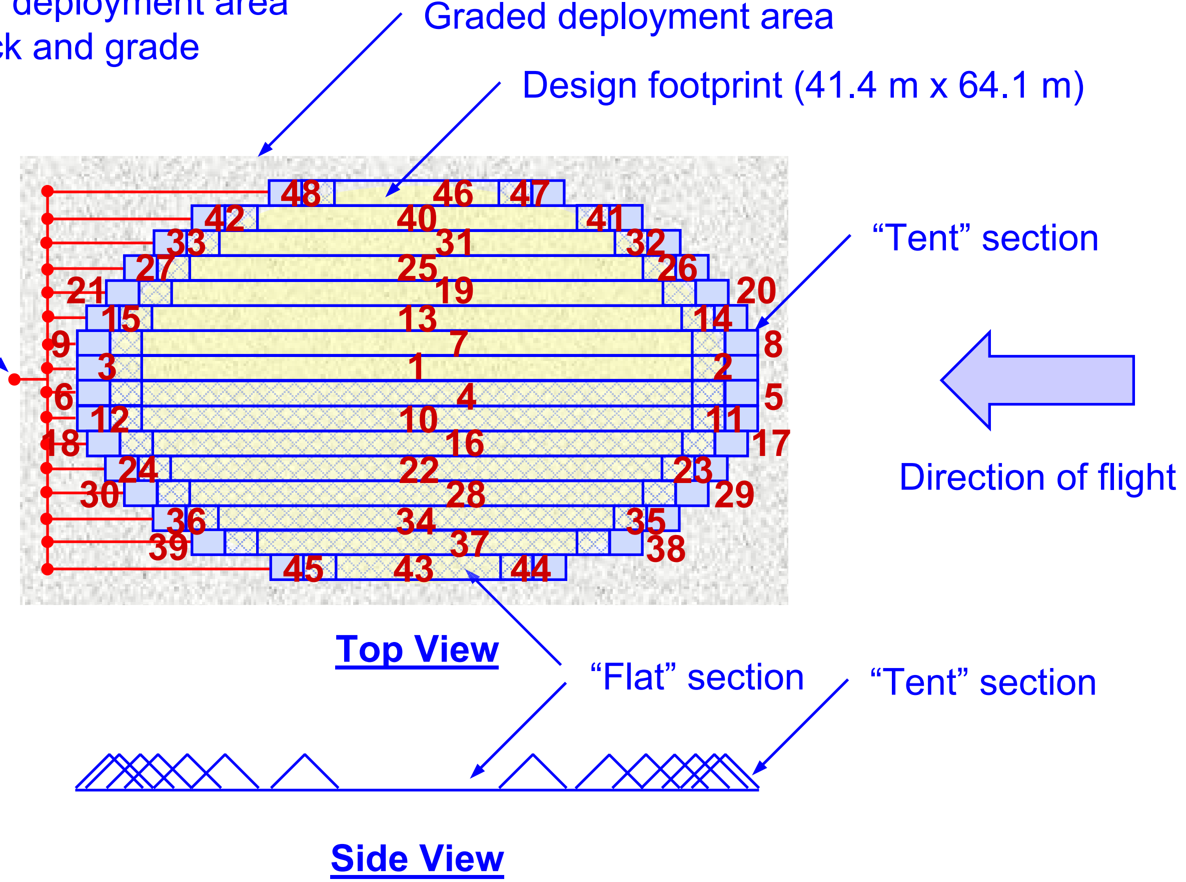
Deployed and Stowed Surface Receiver Module



Lunar surface receiver module stows into a reasonable sized package, 1 m x 2.5 m x 0.1 m (0.2 m^3) with 71 folds.

Lunar Surface Receiver Deployment Sequence

Step 0 – Align 51 x 81 m deployment area to spacecraft ground track and grade



Lunar surface receiver may be deployed in as few as 50 steps. Each module deploys independently and can be stowed via refolding.

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Surface Element Energy Storage and Power Trade

	Power		Mass			
Energy Storage	Charge	Total	Collector	E-Storage	Total	Comments
kW-hr	kW_e	kW_e	kg	kg	kg	
151	15	20	4,572	755	5,327	
240	10	15	3,429	1,200	4,629	
400	4	9	2,057	2,000	4,057	
500	2	7	1,600	2,500	4,100	
525	1	6	$\boxed{1,372}$	$\boxed{2,625}$	$\boxed{\mathbf{3,997}}$	minimum charge power

- **Total of ~ 4 MT and 3.3 m^3 (stowed volume) lunar surface receiver and 525 kW-hr battery are required for a continuous 5 kWe output**
  - **~2/3 of the total mass results from battery**

- **Receiver (41 m x 64 m) can generate > 500 kWe during daytime**

Power beaming configuration can reduce energy storage requirement by 70%

Proposed Technology Development

Current State-of-the-Art – CIGS PV Arrays

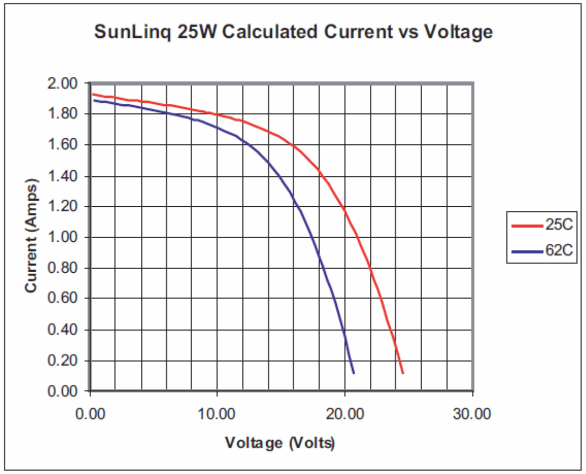
Thin Film PV Array can be deployed by two crew members

Current State-of-the-Art – CIGS PV Arrays (concluded)

Electrical Characteristics*	
SL Product Number	SL - 25
Nominal System Voltage Rating	12V
Nominal Rated Power (watts) at STC	25
Nominal Rated Voltage at MPP (VDC) at STC	16.5V
Nominal Rated Current (amps)	1.5
Open Circuit Voltage (volts)	25
Short Circuit Current (amps)	2.1
Thermal Characteristics	
Temperature Coefficient for Power (%/C)	-0.6
Temperature Coefficient for Voltage (%/C)	-0.5
Temperature Coefficient for Voc (%/C)	-0.4
Cell Temperature Operating Range	- 40^0 F to 176^0 F / - 40^0 C to 80^0 C
Dimensions and Weight	
Folded	
Length, in (mm)	11 (279)
Width, in (mm)	8.25 (210)
Thickness, in (mm)	.7 (17.78)
Unfolded	
Length, in (mm)	41 (1048)
Width, in (mm)	21.5 (546)
Thickness, in (mm)	0.03 (.762)
Weight	
Weight, lb (kg)	1.8 (.82)
Power to weight ratio watt/lb (watt/kg)	13.9 (30)

*Data at Standard Test Conditions (STC)

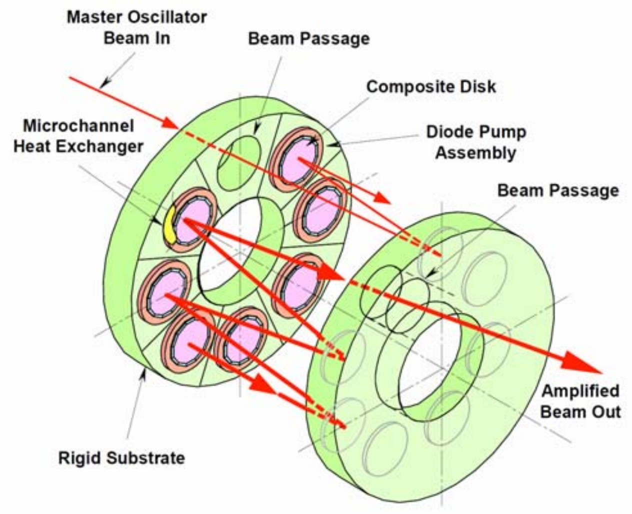
STC: irradiance level 1000W / m^2, spectrum AM 1.5 and cell temperature 25^o C
The thin film solar material in this module can increase in power with exposure to sunlight. Expose the module to sunlight for 3-4 days for best measurement results.
Rating tolerance +/- 15%



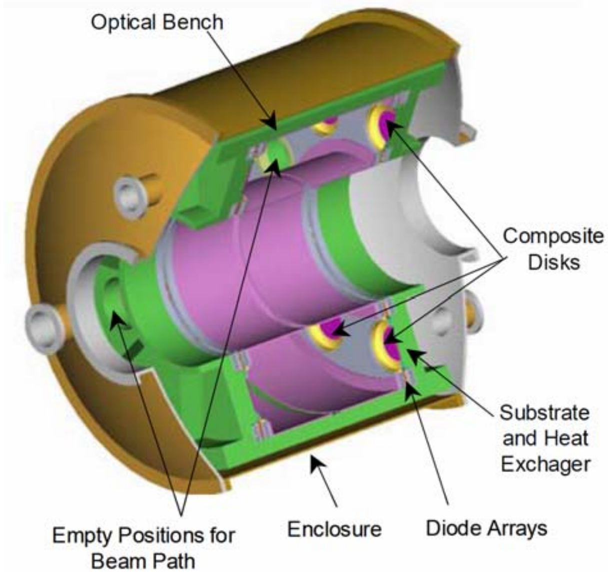
The I/V graph above shows the typical performance of the solar module at STC

- *Recent NREL report of 15% efficiency for CIGS*
- *Expect efficiency to be 20% by 2015 - 2018*

Boeing Solid-State Disk Laser Concept (June 2008)



Axisymmetric layout showing multiple disks mounted on a common substrate

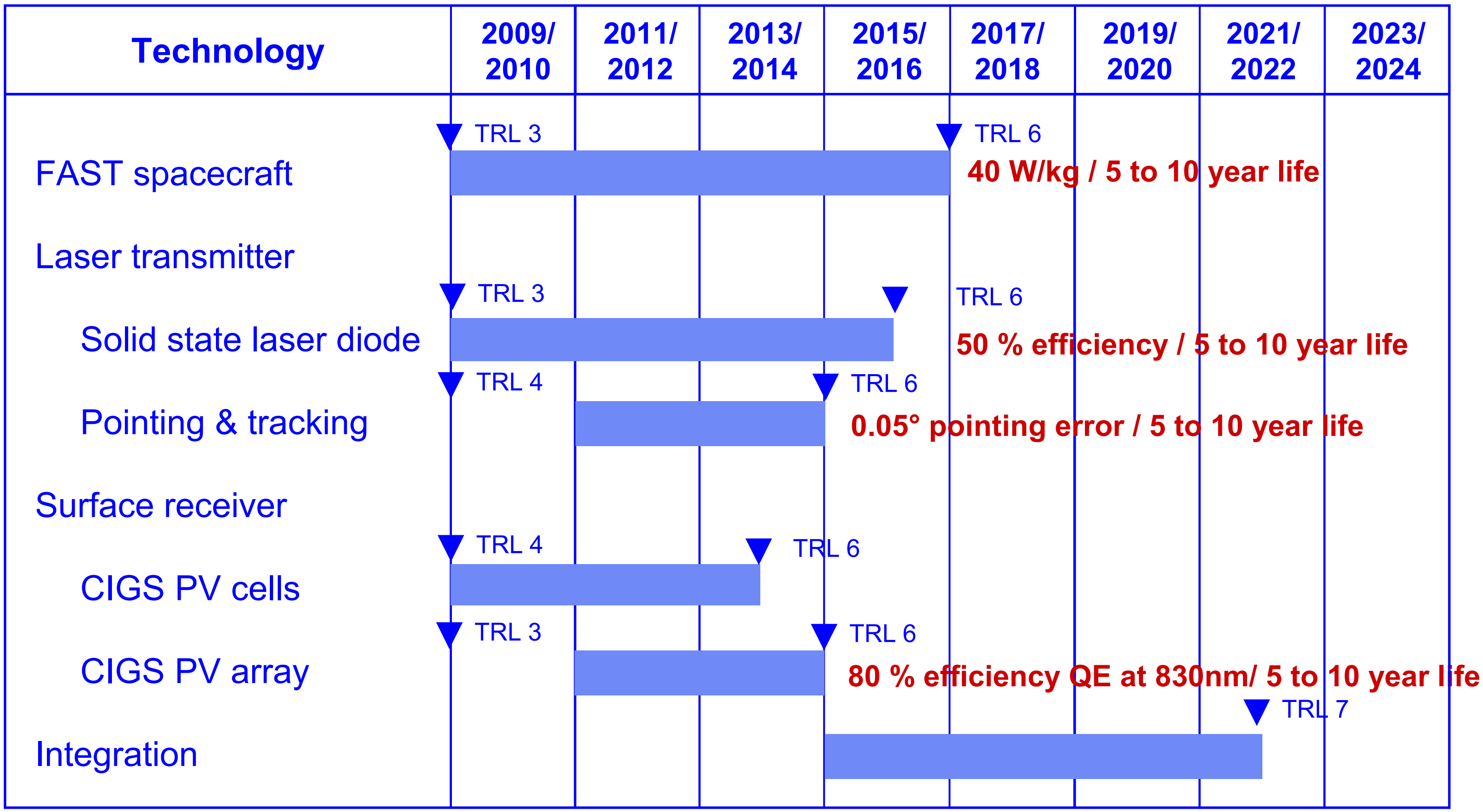


Laser Subsystem Engineering Concept

– 25 kW thin-disk, solid-state tactical laser system

- Scalable to a 100-kW-class system based on the same architecture and technology
- Giving the warfighter an ultra-precision engagement capability
- Incorporates COTS, SOTA lasers used in the automotive industry
  – Have demonstrated exceedingly high reliability, supportability and maintainability

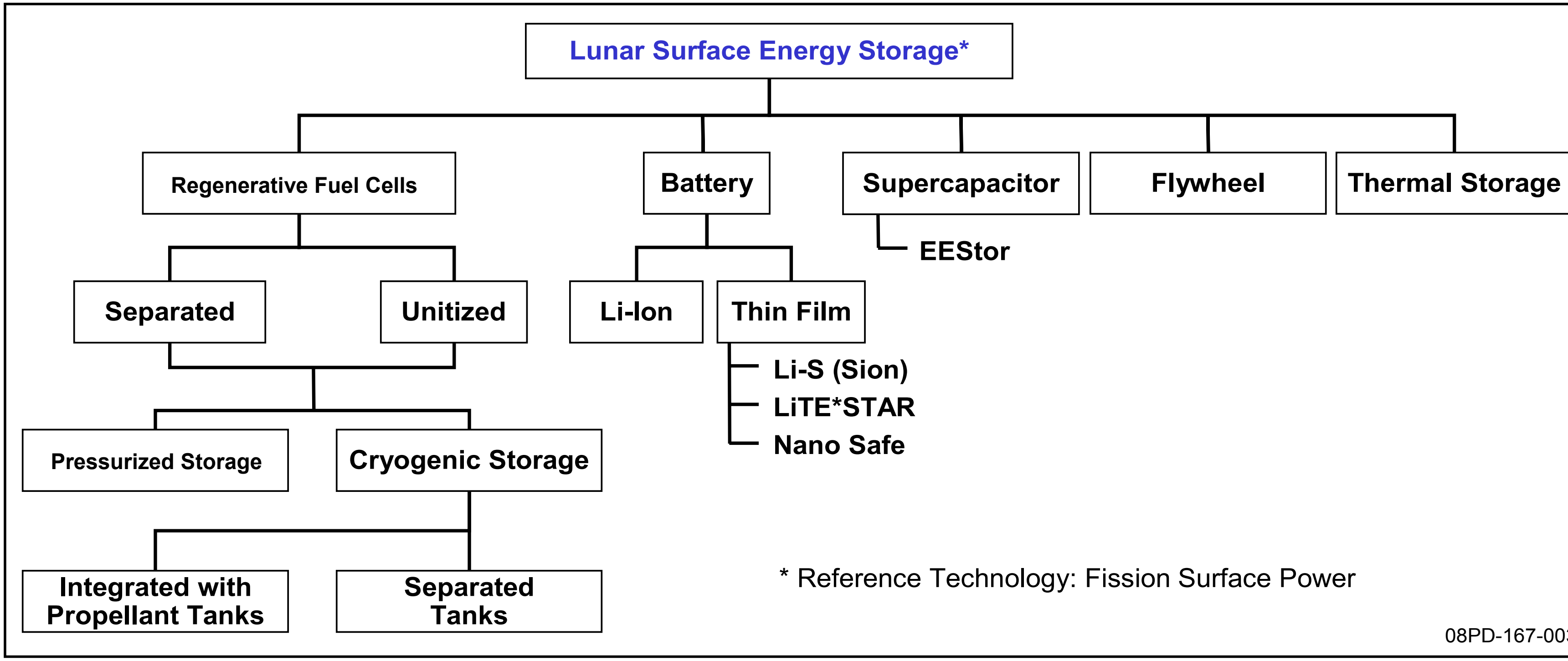
Laser Power Beaming Technology Roadmap



Roadmap to achieve laser power beaming technology by 2018

Task II
Other Surface Energy Storage Technologies for Comparison

Surface Energy Storage Technology Trade Space



Trade Case and Assumptions

Power (to user)	kWe	5
Moon Sidereal Periods	hours	708.7
Lunar Eclipse	hours	354.0
Lunar Sunlit	hours	354.7
Total ES	kW-h	2,000
Lunar Night Sink T	K	100
Lunar Day Sink (with Apron)	K	250
Solar Insolation	W/m^2	1,367

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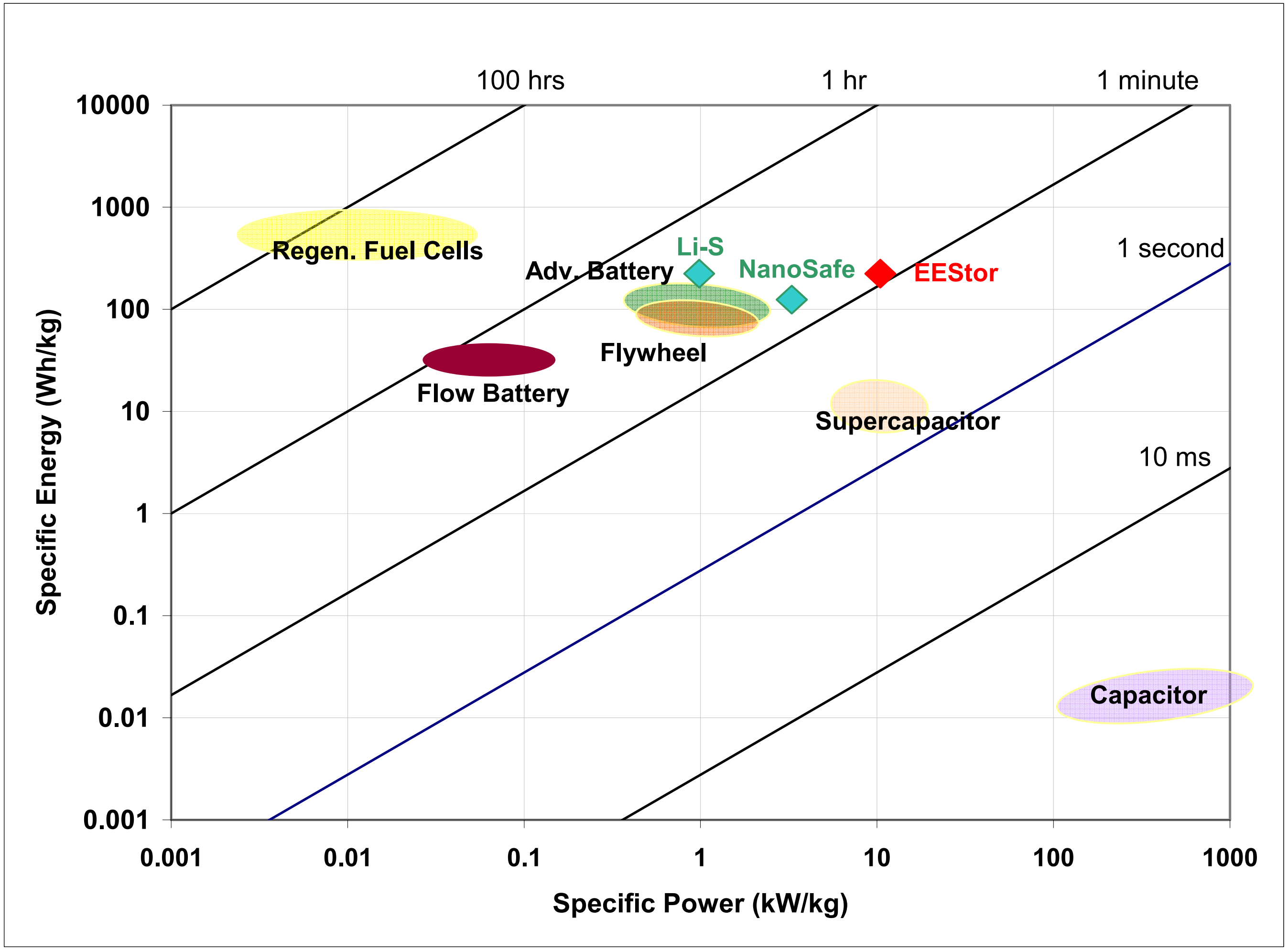
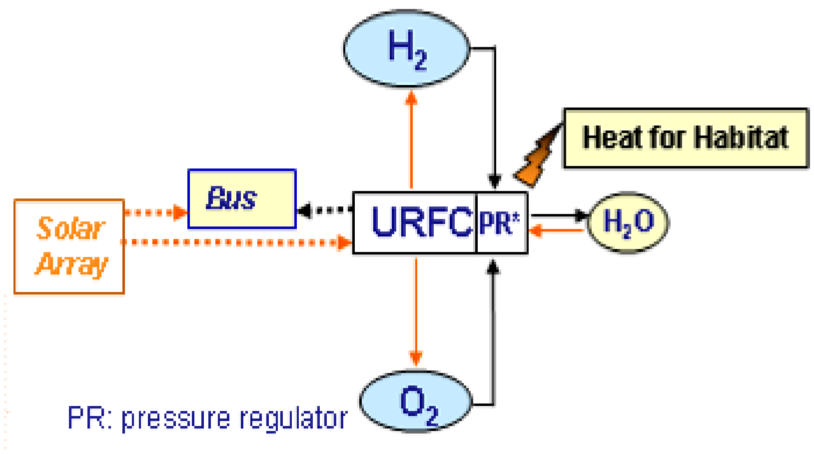
Regone Plot of Energy Storage Technologies

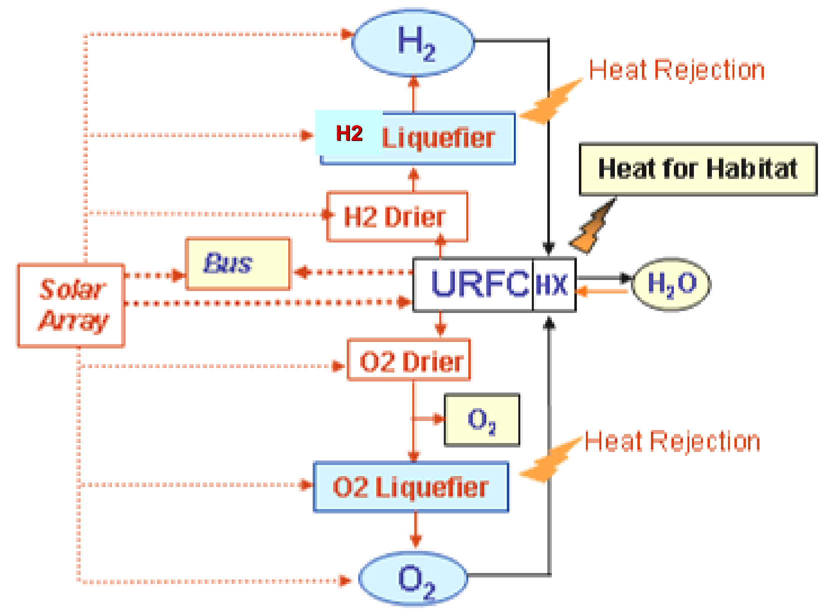


Regenerative fuel cell (RFC) is suitable for long duration energy storage

RFC with High Pressurized and Cryogenic Reactant Storage



Schematic of RFC with pressurized tank storage



Schematic of RFC with cryogenic storage

	State of the Art			Advanced	
	PEM FC PEM Electrolysis H P Storage	AFC PEM Electrolysis H P Storage	Unitized Regen. Fuel Cell (URFC) H P Storage	Advanced URFC Cryogenic Storage	AFC or HE PEMFC PEM Electrolysis Cryogenic Storage
FC Efficiency (%) @BOL	54	65	50	54	70
Electrolysis Efficiency (%)	93	93	90	93	93

SOTA AFC provides highest FC efficiency & PEMFC needs to improve efficiency

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Various RFC Configurations CBE Mass Data & TRL

	Regenerative Fuel Cell				
	State of the Art			Advanced	
	PEM FC PEM Electrolysis H P Storage	AFC PEM Electrolysis H P Storage	Unitized Regen. Fuel Cell (URFC) H P Storage	Advanced URFC Cryogenic Storage	AFC or HE PEMFC PEM Electrolysis Cryogenic Storage
FC Efficiency (%) @BOL	54	65	50	54	70
Electrolysis Efficiency (%)	93	93	90	93	93
RFC RT Efficiency (%)	50	60	45	50	65
Power for Charging (kWe) based on power input	10.5	8.7	11.7	10.5	8.1
FC Specific Power (kW/kg) based on power output	0.167	0.102			0.102
Electrolysis Specific Power (kW/kg) based on power for charging	0.75	0.75			0.75
RFC Specific Power (kW/kg) based on power output	0.116	0.083	0.0565	0.09825	0.084
FC Operating T (oC)	80	80	90	120	120
Reactant Usable (%)	95	95	95	95	95
Working Performance Factor for Hydrogen Tank (379330 psi-in3/lb)	379330	379330	379330		
Working Performance Factor for Oxygen Tank (379330 psi-in3/lb)	379330	379330	379330		
controls, and instrumentation) (kW/kg) based on power output	0.06	0.06	0.06	0.05	0.05
	Mass (kg)	*Mass (kg)*	*Mass (kg)*	*Mass (kg)*	*Mass (kg)*
RFC	46	63	93	54	62
Radiator	15	10	16	10	5
Reactant (H2)	112	93	125	112	87
Reactant (O2)	897	745	1001	897	692
Tanks	2732	2312	3238	467	393
Structure, ancillary components, piping, controls, and instrumentation	83	83	83	125	108
PMAD	10	10	10	10	10
Drying/Liquification equipment				132	104
Power for cryogenic storage				338	267
Others (additional radiator, piping)				19	10
Additional Solar Array Power for Energy Storage	31	26	35	22	17
Additional PMAD	5	4	6	5	4
TOTAL Mass	3931	3347	4607	2191	1760
Specific Energy (W-h/kg), based on energy output	509	598	434	913	1137
TRL	> 5	> 5	5	3	3

Regenerative Fuel Cell with Cryogenic Storage has potential to provide > 1000 W-hr/kg for Lunar surface energy storage

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Li Based Battery Mass Data

Type	Specific Energy (W-hr/kg)	Cycles (#)
Li Based Battery (SOTA)		
Li-Ion	> 200	> 2,000 (DOD of 80%)
Li Based Battery (Advanced, by 2015)		
Thin Film Li Sulfur (Sion Power)	> 300	Currently low cycles Improvement expected
LiTE*STAR Thin film Li-Polymer Solid State (Infinite Power Solutions/ORNL)	300	70,000

- Li battery technology has been advanced quickly: 3X in 10 years
- Estimated at >300 W-hr/kg by 2015, Sion Power's Li-S battery is a promising battery technology,
  - (SOTA) Li-S suffers low efficiency (80% vs. >98% of Li-ion battery) and low cycle life

Task 2 CBE Mass Data & TRL for Surface ES Technologies (other than FC based)

	State of the Art		Advanced				
	Li-Ion Battery	Flywheel	Li Polymer Battery*	Thin Film Li Sulfur (Sion Power)	Battery-Supercapacitor Hybrid EEStor	Thermal Storage	FSP*
RT Efficiency (%) @ BOL	95	92	99	80	98		
DOD (%)	80	80	90	90	95		
Power for Charging (kWe) based on power input	6.9	7.1	5.9	7.3	5.6		
Battery (kW-hr/kg)	0.150	0.100	0.240	0.320	0.224		
Operating T (oC)	40	60	120	65	40		
Structure, controls \and instrumentation (kW/kg)	0.02	0.03	0.02	0.02	0.02		
	Mass (kg)	*Mass (kg)*	*Mass (kg)*	*Mass (kg)*	*Mass (kg)*		
Energy Storage	17544	27174	9353	8681	9590		
Radiator	2	2	2	2	2		
PMAD	10	10	10	10	10		
Structure, ancillary components, piping, controls, and instrumer	250	166.6666667	250	250	250		
Additional Solar Array Power for Energy Storage	20	21	17	22	17		
Additional PMAD	3	4	3	4	3		
TOTAL Mass	17830	27377	9635	8968	9872	18460	< 3,000
Specific Energy (W-h/kg), based on energy output	112	73	208	223	203	108	> 600
TRL	> 6	> 6	5	4	4	> 6	4 to 5

- **Note: mass data is extrapolated from a 40 kWe FSP.**

Advanced (TRL>6 between 2015 to 2018) energy storage technologies, other than RFC, can achieve ~200 W-hr/kg

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Summary of Task II Energy Storage Technology Trade Results

	Lunar Surface Energy Storage	Technical Performance				
	Technologies	Specific Energy (CBE - W-hr/kg)	System Efficiency, Not Including Waste Heat Application (%)	Energy Density (W-hr/l) / Volume	Failure Tolerance	Risk (TRL)
SOTA	RFC (AFC) w Pressurized Storage	705	60	> 200	Medium	> 5
	Li-Ion	112	95	< 350	High	> 6
	Flywheel	73	92	< 200	Medium	> 6
Advanced	RFC (AFC) w Cryogenic Storage	1153	65	> 1000	Medium	3
	Li-Polymer	208	99	< 600	High	5
	Thin Film Li-S Battery	223	80	< 600	High	4
	EEStor	203	98	> 1000	High	4

- **RFC with cryogenic storage is a preferred lunar surface energy storage technology**
- **AFC or high efficiency PEMFC is recommended as the fuel cell technology**
  - **AFC suffers life issue**
  - **High efficiency PEMFC development is required: from 55% (SOTA) to 70%**
- **Cryogenic storage of RFC reactants reduces mass by a half and volume by 4X comparing with high pressure storage RFC configuration**
- **Waste heat from relative less efficient RFC can be integrated with ECLSS**
- **Due to its limited applications, the RFC technology may require more funding to develop in order to achieve TRL > 6 by 2015**

RFC with Cryogenic Storage is preferred for lunar surface energy storage

Summary of Power Beaming vs. Ad. RFC w/ Cryogenic Storage

Lunar Surface Energy Storage	Technical Performance								Programmatic	
Technology	Element	Mass (CBE) (kg)	Stowed Volume (W-hr/l)	Oper. Effect. (mobility)	Specific Energy (CBE) (W-hr/kg)	* Sys. Eff. (%)	Redu nd-ancy	Risk (TRL)	Rel. Dev. Cost	Integration with Other Systems
Power Beaming (one spacecraft)	Space	1,000	N/A	High	N/A	30 x 50	Low	3	Med.	Telecom.
	Surface	3,997	720	Med.	500	50	High	3	Low	
Power Beaming (two spacecrafts)	Space	2,000	N/A	High	N/A	30 x 50	High	3	Med.	Telecom.
	Surface	3,997	720	Med.	500	50	High	3	Low	
RFC (cryogenic storage)	Surface	1,735	> 1,000	Low	1,153	30 x 65	Med.	3	Med.	ECLSS, Ascent Propellant, ISRU

* Spacecraft power system (PV array) and laser; RFC power system (PV array) and fuel cell, respectively

- From mass point of view, power beaming is no better than RFC technology
- Power Beaming has advantages of mobility & redundancy (for 2 s/c case)
- Power Beaming and RFC w/ cryo. storage are at low TRL (3: proof of concept)
  - Expect both require relative medium development cost comparing with FSP
- Both are highly "integrate-able" with other subsystems for optimal application

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Study Conclusions

- Laser power beaming provides a feasible option for lunar energy storage
  - Key benefits include added value of mobility and integration of telecom.
  - A two spacecraft configuration is recommended due to redundancy
  - A near optimal configuration includes orbital period of 16.1 hours which results in a “gap” in coverage of less than 16 hours
    - A surface energy storage on the order of 525 kW-hr, for 5 kWe continuous power, which reduced requirement by > 70%
  - Laser power beaming & CIGS PV receiver provides the smallest footprint
  - Recommend developing DARPA FAST spacecraft with electric propulsion
  - For min. mass, power beaming is no better than Regenerative Fuel Cells

- Regenerative Fuel Cells with cryogenic reactant storage is a feasible and preferred lunar surface energy storage tech
  - High eff. FC, Alkaline FC or PEM FC, is required

Recommendations for Forward Work

- **Continue study of spacecraft laser power beaming technologies**
  - Power generation, PMAD, laser beam generation and transmission, thermal management for the laser subsystem, and laser beam pointing and tracking
  - Investigate alternative orbit strategies (than "frozen orbit"), such as matching the precession rates of the moon, to maximize coverage time
- **Conceptual synthesis of laser telecom with laser power beaming**
- **Perform a subscale laser photovoltaic ground demonstration**
  - Demonstration performed in a simulated space environment and include the 830 nm solid state laser diode and CIGS photovoltaic array receiver subsystem technologies

- **Demonstrate Regenerative Fuel Cells with cryogenic reactants storage**
  - Optimal assembly, more reliable & failure tolerance, to get TRL > 6 by 2018

- **Initiate an integrated study for resources of "Just-in-time resource management"**
  - Study of optimal usage of limited resources for Altair, Habitation/ECLSS, Energy Storage, Ascent Propellants, ISRU
    - Six essential compounds: H_2, O_2, H_2O, CH_4, CO_2 and CO

Lunar Resource Management Study

- <u>Objective</u>

Study of optimal usage of limited resources for Altair and Lunar Outpost

- <u>Study Case</u>
- Six compounds are essential for various Altair/Outpost subsystems
  - H_2, O_2, H_2O, CH_4, CO_2 and CO
  - Habitation/ECLSS, Energy Storage, Ascent Propellants, ISRU
- All can be produced with others as reactants <u>at various temperature</u> ranges, <u>with energy generated or required</u>
  - Reforming $2CH_4 + O_2 \Rightarrow 2CO + 4H_2$
  - Shift $CO + H_2O \Rightarrow CO_2 + H_2$
  - Reversed Shift $CO_2 + H_2 \Rightarrow CO + H_2O \Rightarrow CO + H_2 + \frac{1}{2} O_2$
  - Sabatier $CO_2 + 4H_2 \Rightarrow CH_4 + 2H_2O \Rightarrow CH_4 + 2H_2 + O_2$

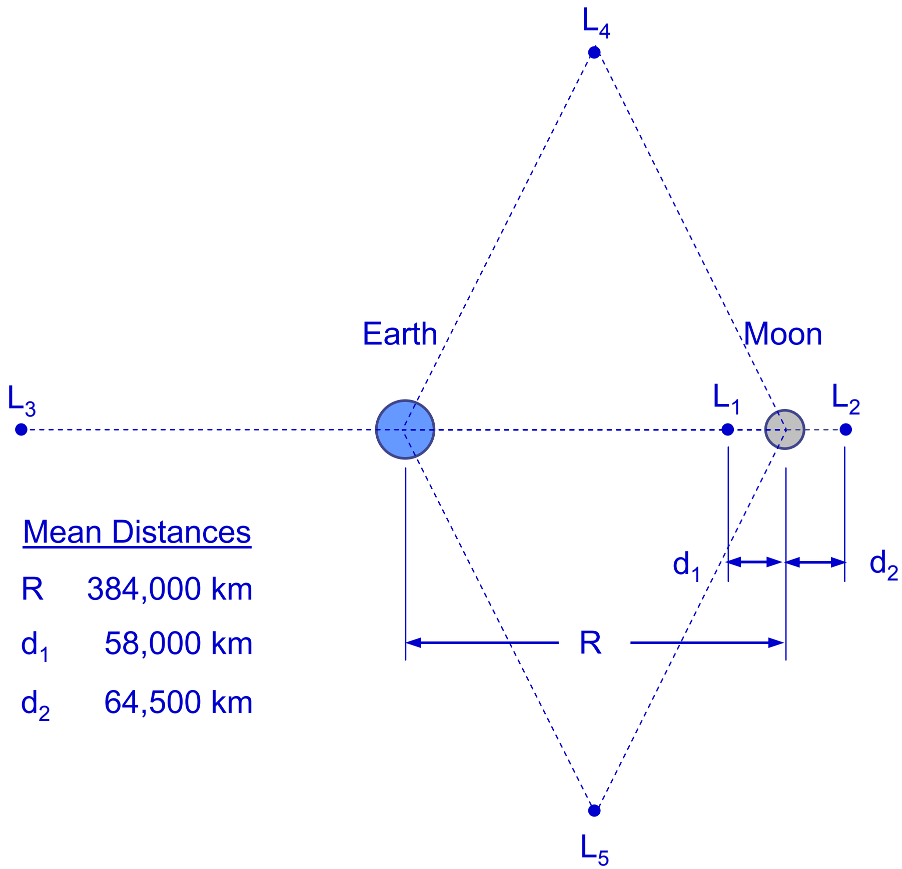
$$CH_4 \Downarrow C + 2H_2$$

$$C + CO_2 \Rightarrow 2CO$$

  - ISRU FeO (from Moon) + $H_2 \Rightarrow Fe + H_2O$
- How to mange these resources for "<u>just-in-time resource management</u>" is the goal of this integrated study

Backup

Libration Points in the Earth-Moon System



<u>Mean Distances</u>

R	384,000 km
d_1	58,000 km
d_2	64,500 km

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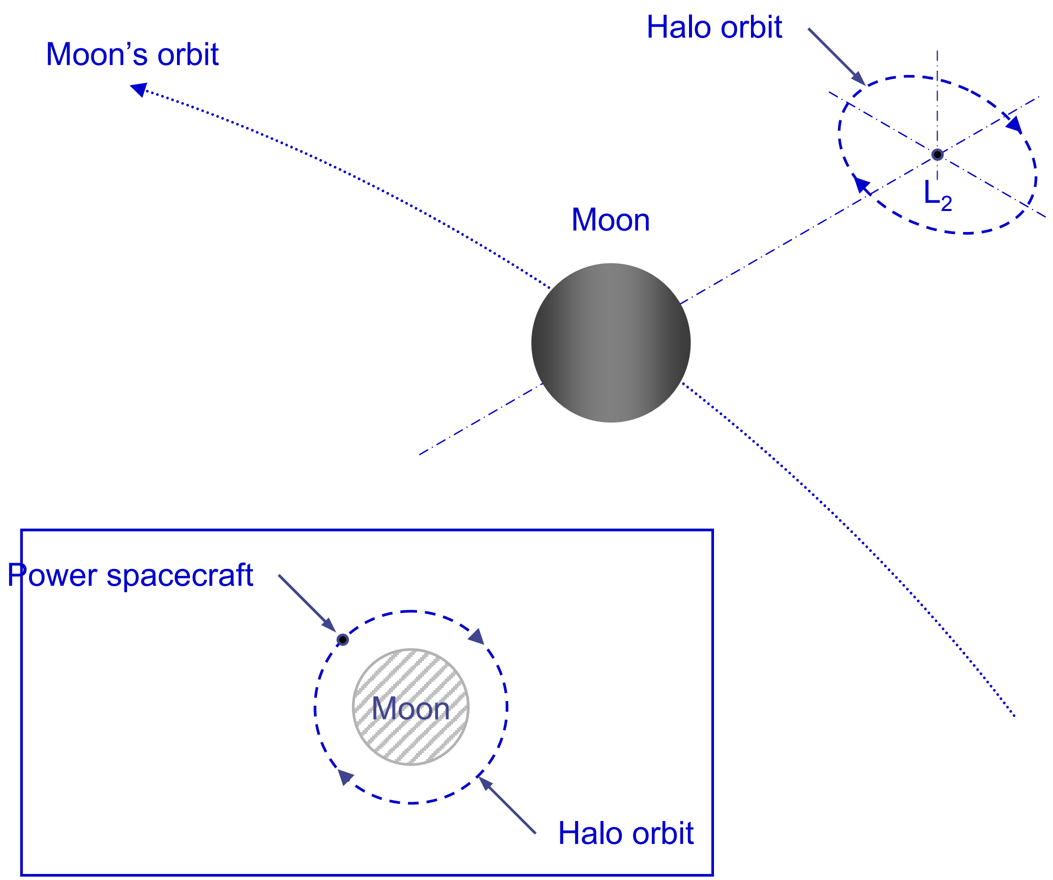
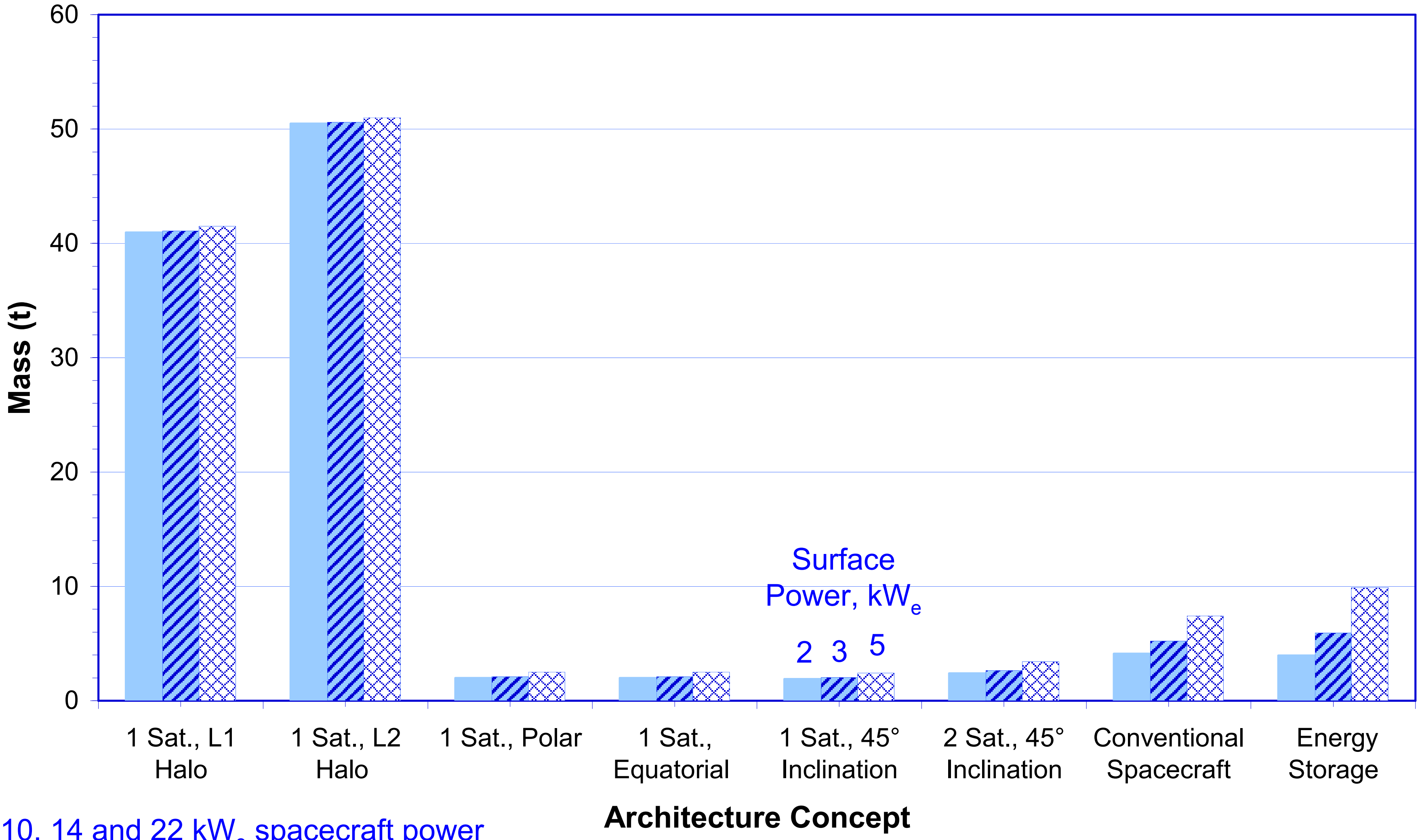
Representative Earth Lunar Libration Point Halo Orbit

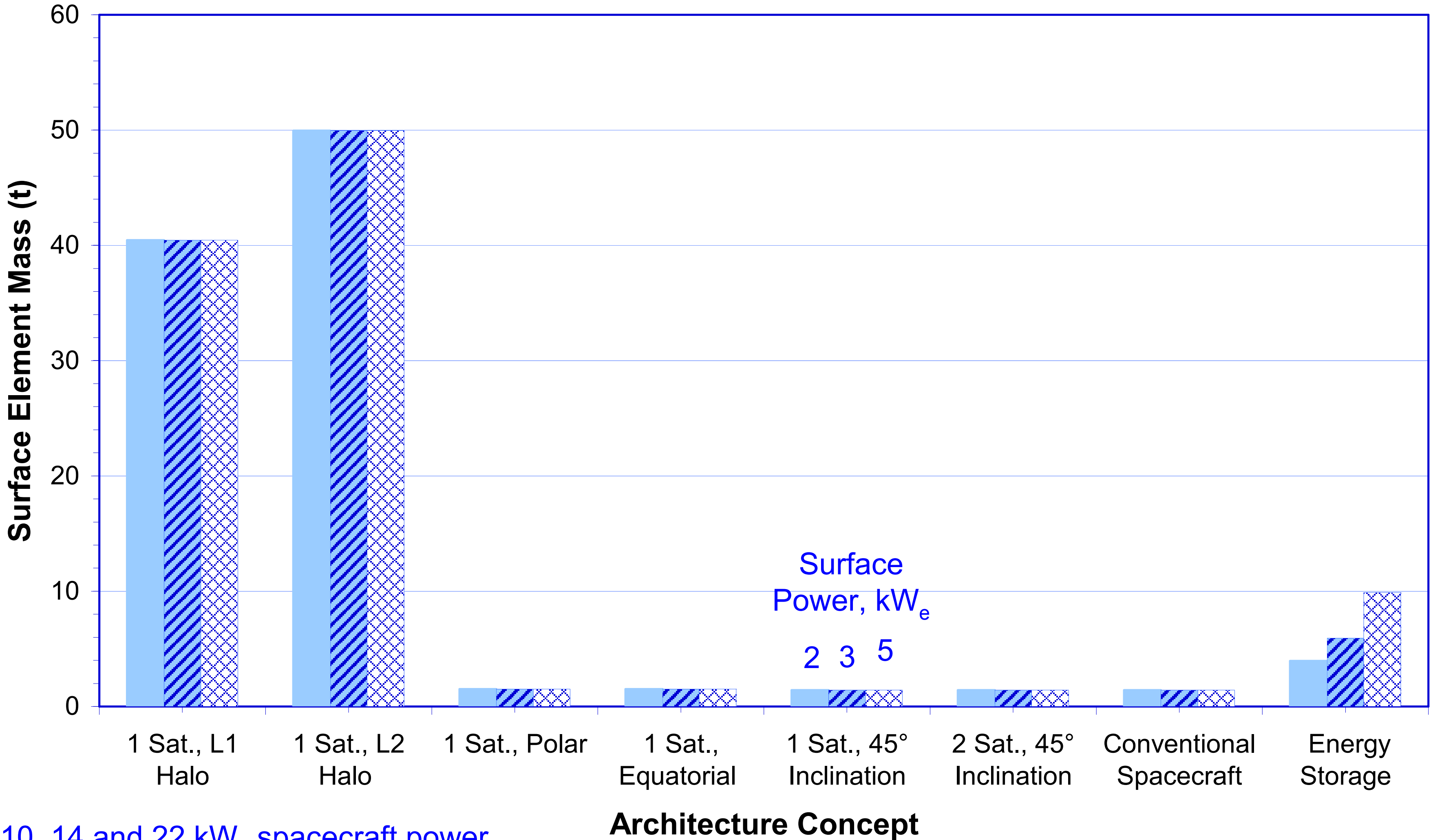


Total Mass – 2 to 5 kW_e Surface Power



10, 14 and 22 kW_e spacecraft power

Surface Element Mass – 2 to 5 kW$_e$ Surface Power



10, 14 and 22 kW$_e$ spacecraft power

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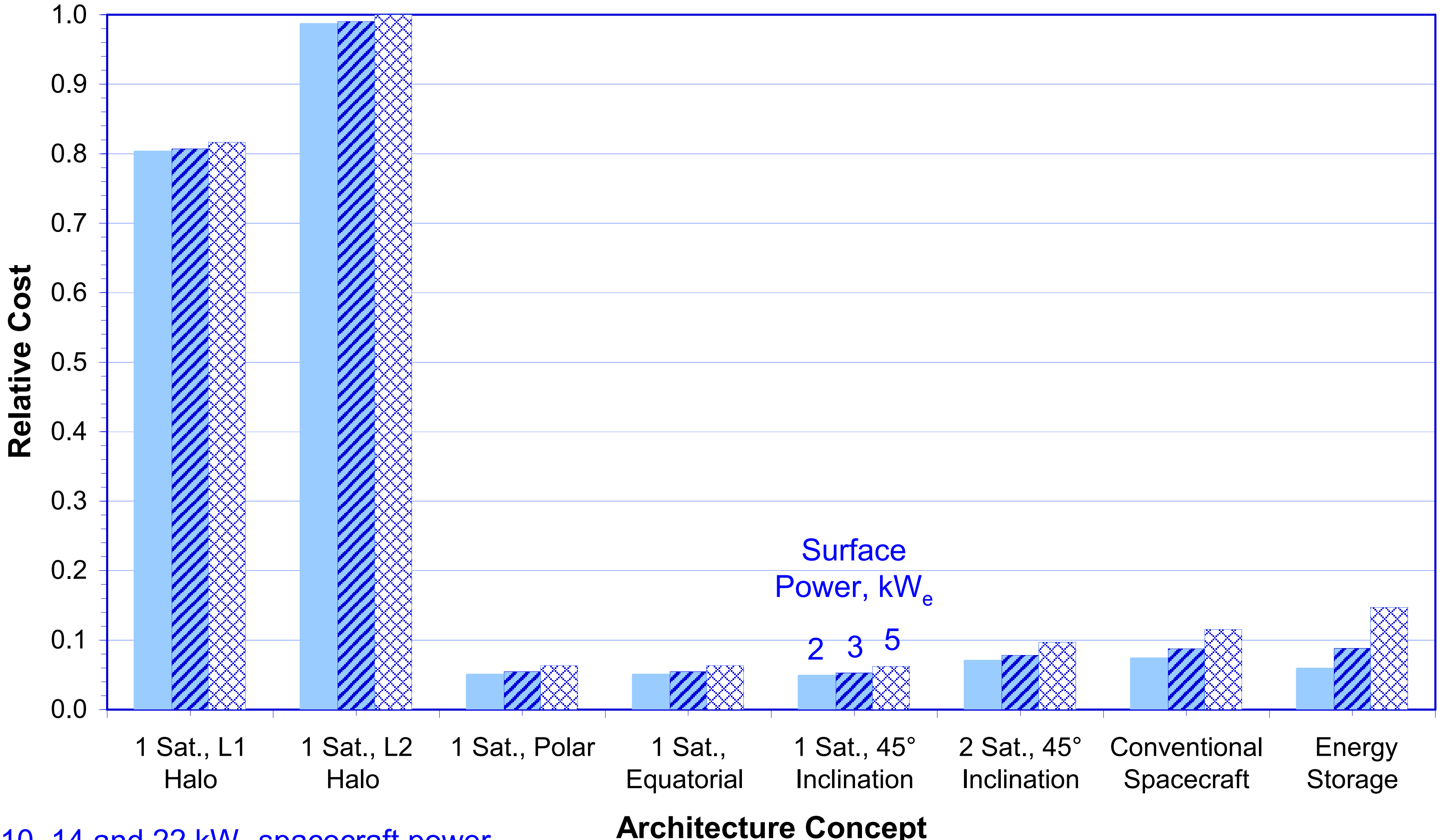
Relative Cost Comparison – 2 to 5 kW_e Surface Power



10, 14 and 22 kW_e spacecraft power

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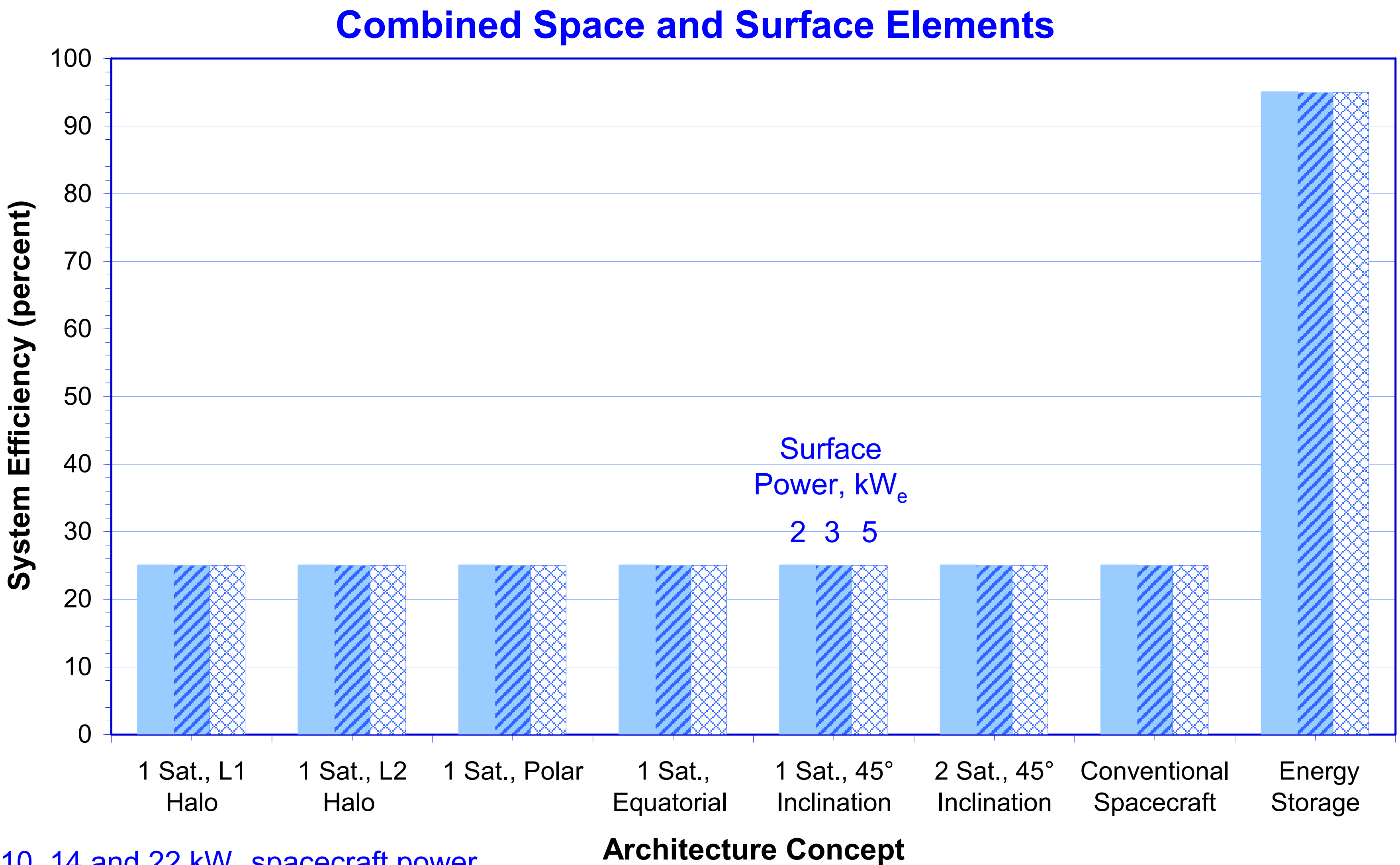
System Efficiency – 2 to 5 kW$_e$ Surface Power



10, 14 and 22 kW$_e$ spacecraft power

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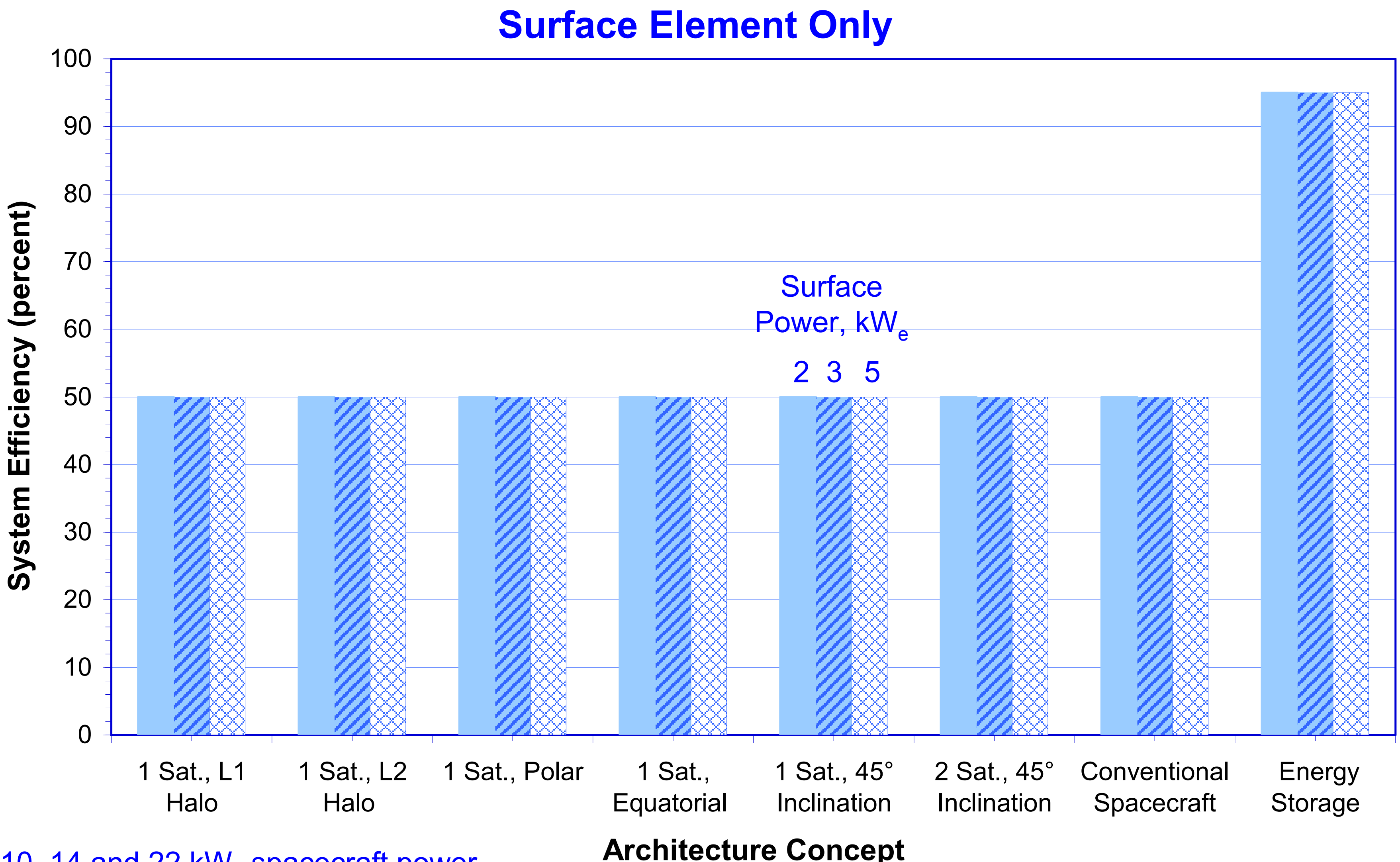
System Efficiency – 2 to 5 kW$_e$ Surface Power



10, 14 and 22 kW$_e$ spacecraft power

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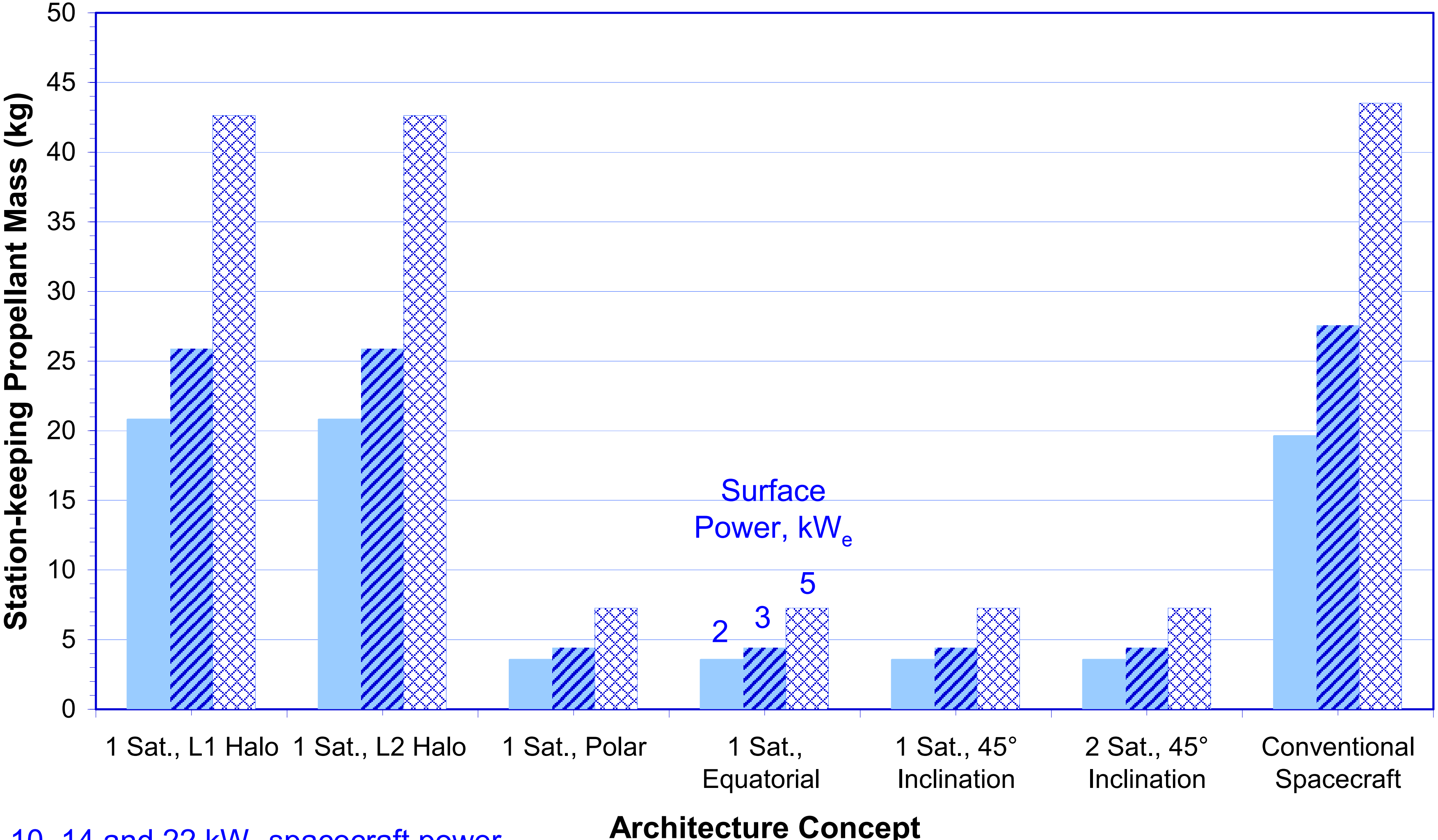
Propellant Mass – 2 to 5 kW$_e$ Surface Power



10, 14 and 22 kW$_e$ spacecraft power

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Candidate Orbits

Alt p	Alt a	R p	R a	a	e	V p	V a	Period	Inc
km	km	km	km	km	-	km/s	km/s	hours	deg
11,041	11,041	12,777	12,777	12,777	0.000000	0.619	0.619	36.000	90.000
8,015	8,015	9,751	9,751	9,751	0.000000	0.709	0.709	24.000	90.000
6,313	6,313	8,049	8,049	8,049	0.000000	0.780	0.780	18.000	90.000

Alt p	Alt a	R p	R a	a	e	V p	V a	Period	Inc
km	km	km	km	km	-	km/s	km/s	hours	deg
11,039	11,039	12,777	12,777	12,777	0.000000	0.619	0.619	36.000	0.000
8,013	8,013	9,751	9,751	9,751	0.000000	0.709	0.709	24.000	0.000
6,311	6,311	8,049	8,049	8,049	0.000000	0.780	0.780	18.000	0.000
5,928	16,149	7,666	17,887	12,777	0.400001	0.946	0.406	35.998	45.000
4,112	11,913	5,850	13,651	9,751	0.400000	1.083	0.464	24.000	45.000
3,091	9,531	4,829	11,269	8,049	0.400000	1.192	0.511	18.000	45.000

a	semi-major axis	Alta	periapsis altitude
e	eccentricity	Altp	apoapsis altitude
Vp	periapsis velocity	Rp	periapsis radius
Va	apoapsis velocity	Ra	apoapsis radius
Period	orbit period	Inc	inclination

Candidate Frozen Orbits

Alt p	Alt a	R p	R a	a	e	V p	V a	Period	Inc
km	km	km	km	km	-	km/s	km/s	hours	deg
1,897	6,912	3,635	8,650	6,143	0.4082	1.378	0.579	12.000	45.000
3,025	9,597	4,763	11,335	8,049	0.4082	1.204	0.506	18.000	45.000
4,032	11,993	5,770	13,731	9,751	0.4082	1.094	0.460	24.000	45.000
719	8,090	2,457	9,828	6,143	0.6000	1.787	0.447	12.000	51.707
1,482	11,140	3,220	12,878	8,049	0.6000	1.561	0.390	18.000	51.707
2,162	13,863	3,900	15,601	9,751	0.6000	1.418	0.355	24.000	51.707

a	semi-major axis	Alta	periapsis altitude
e	eccentricity	Altp	apoapsis altitude
Vp	periapsis velocity	Rp	periapsis radius
Va	apoapsis velocity	Ra	apoapsis radius
Period	orbit period	Inc	inclination

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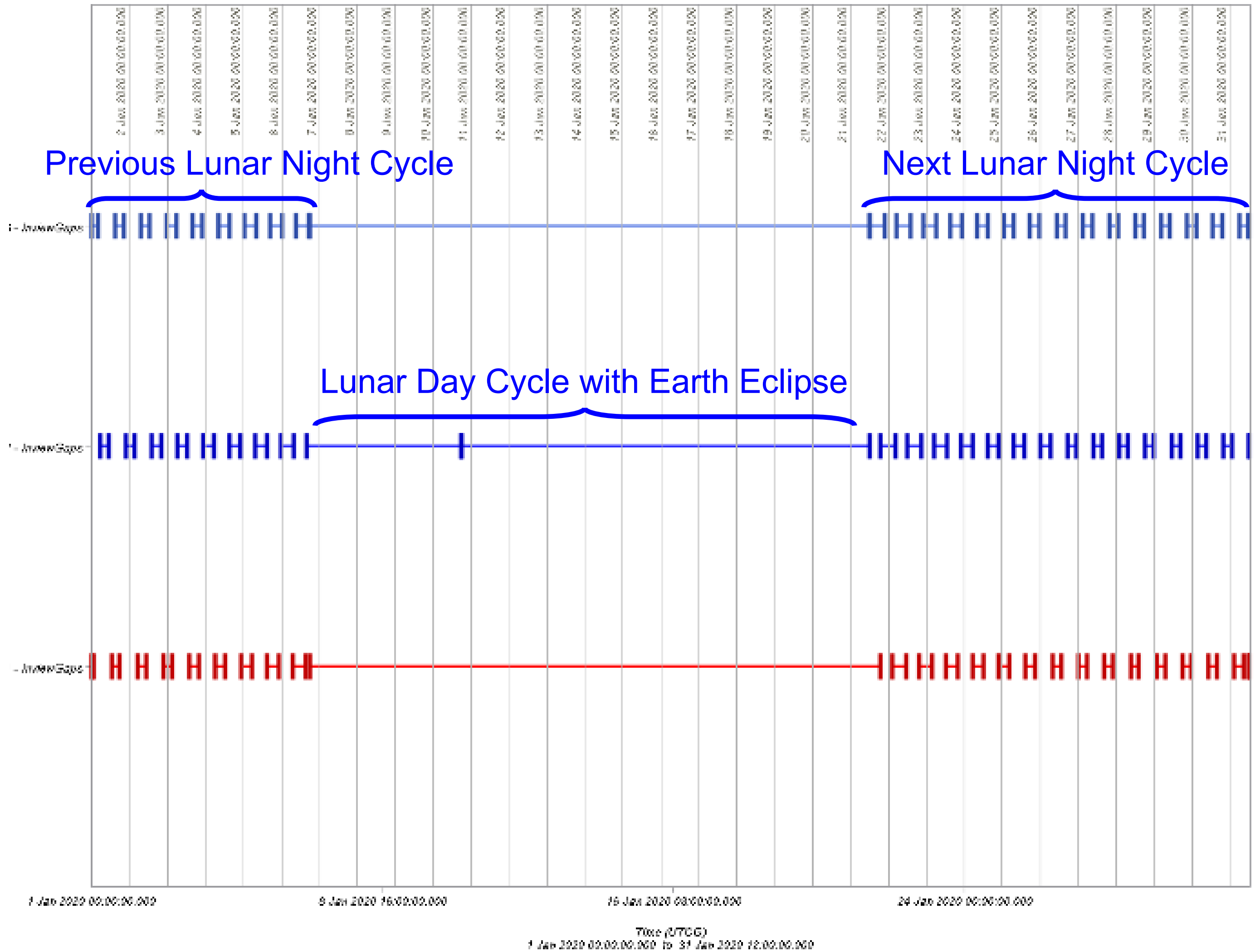
Representative STK Gaps Chart – 3 spacecraft Case



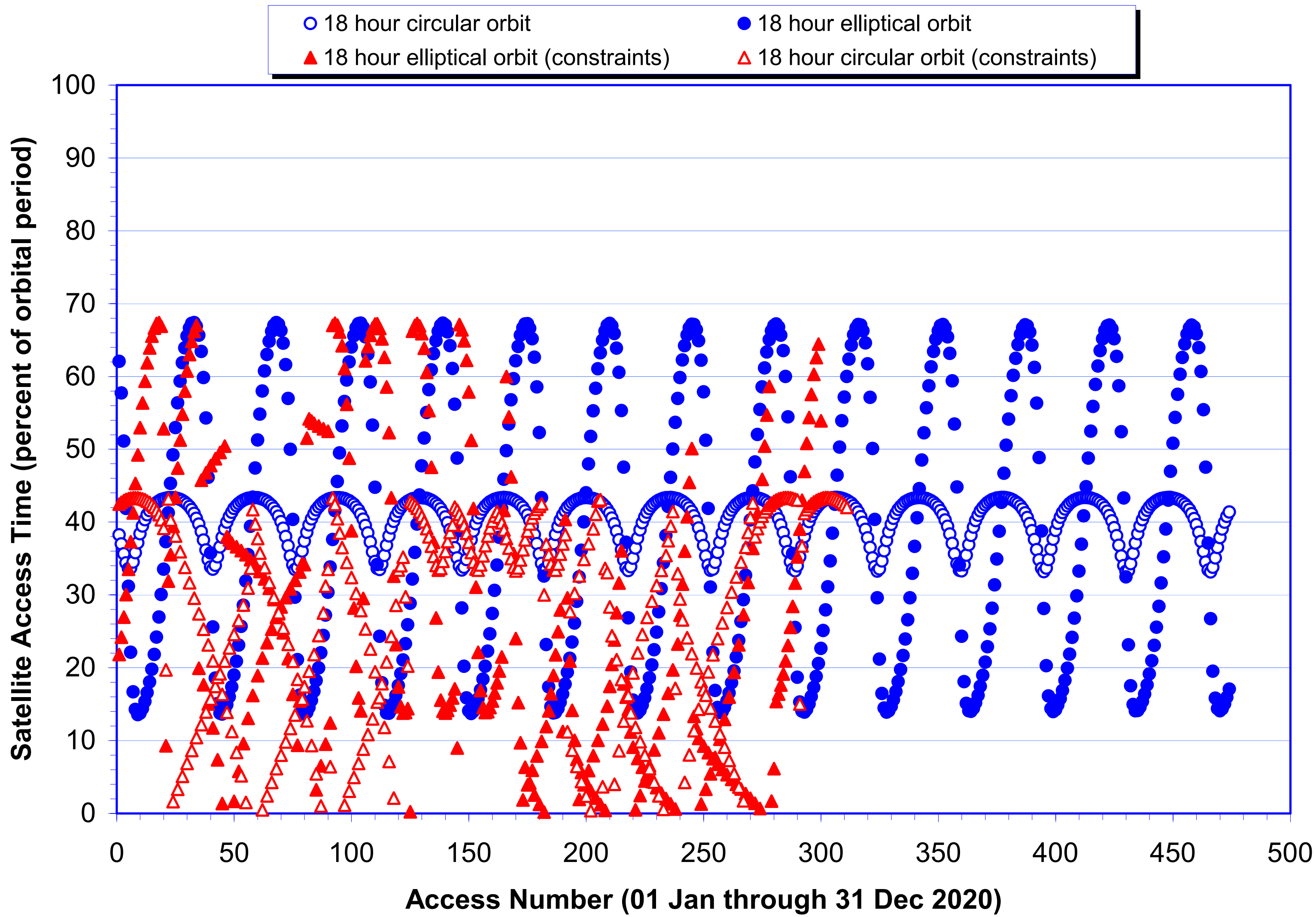
STK v8.1.3 simulation results.

10° latitude, -45° longitude surface site.

AGI spacecraft Tool Kit (STK) Simulation Constraints

- **Unconstrained lighting**
  - Imposed only spacecraft-to-surface line-of-sight constraint
    - A direct line-of-sight must exist between surface site and spacecraft for valid access
- **Constrained lighting**
  - Imposed spacecraft-to-surface line-of-sight constraint
  - Imposed spacecraft sunlight and surface darkness constraints
    - spacecraft must be in direct sunlight and either umbra or penumbra condition must exist at surface site for valid access
- **Lunar surface sites arbitrarily selected to maximize coverage**
  - Initial site and revised surface sites
    - 45° latitude, 60° longitude, 0 km altitude (initially)
    - 10° latitude, -45° longitude, 0 km altitude (revised)
- **Lunar gravity model and orbit propagator**
  - Initially used simple lunar gravity model & low precision orbit propagator
    - Later analysis used high precision orbit propagator (HPOP) with permanent tides
      - Lunar gravity third bodies included Earth and Sun.

Access Summary – 18 hour Orbits



STK v8.1.3 simulation results.

45° latitude, 60° longitude surface site.

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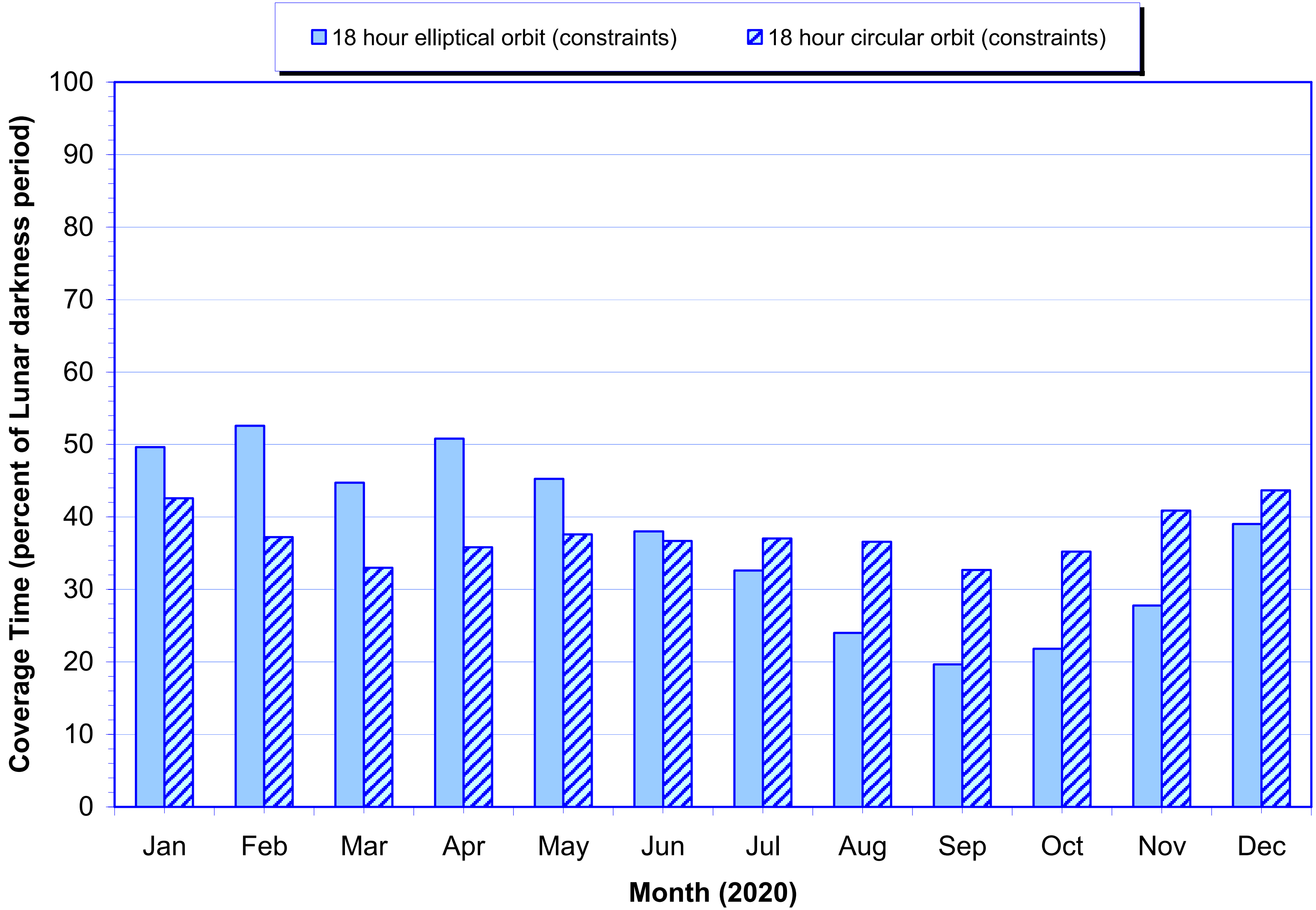
Coverage Summary – 18 hour Orbits



STK v8.1.3 simulation results, 45° inclination orbit.

45° latitude, 60° longitude surface site.

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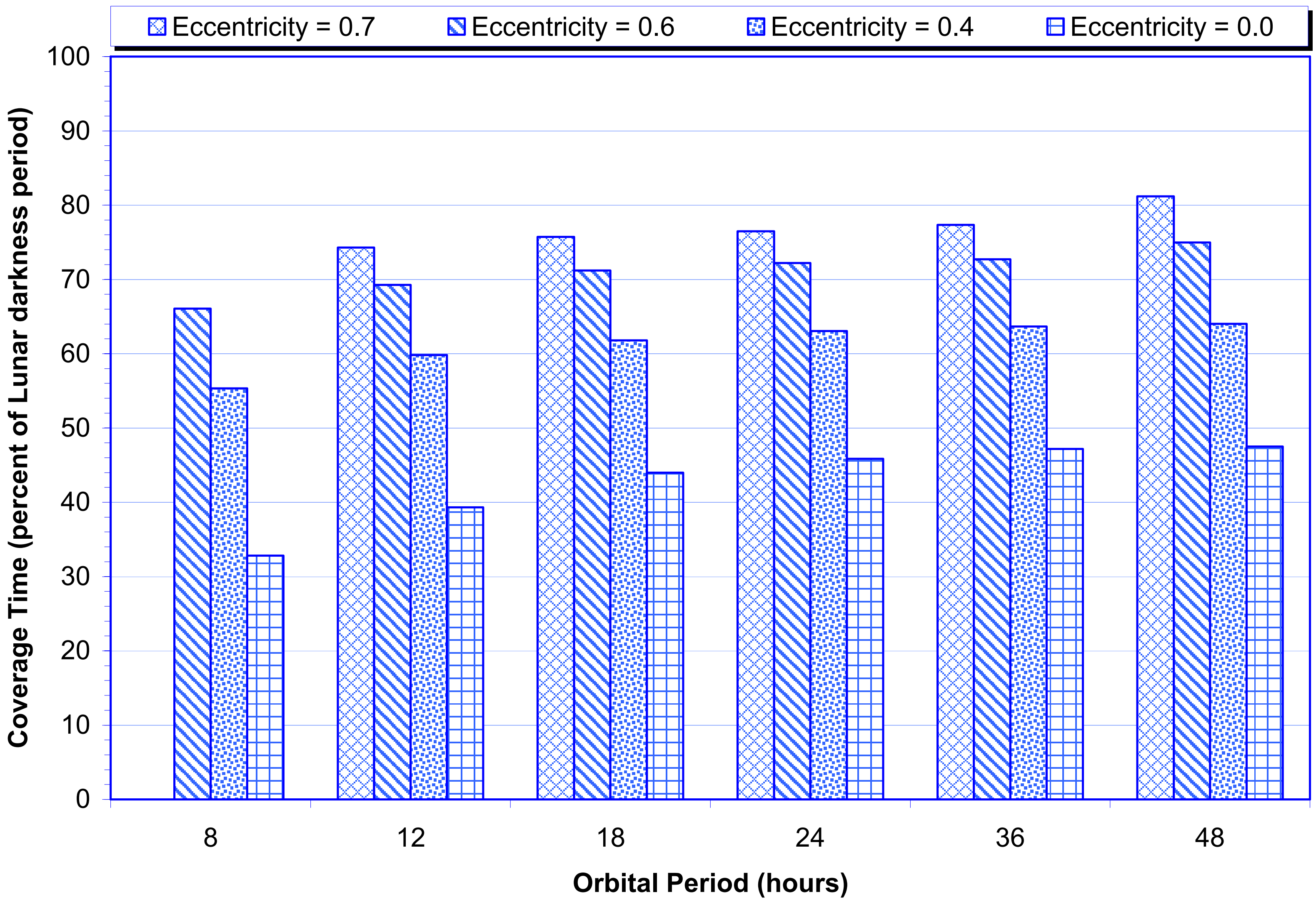
Coverage Summary (Jan 2020, 45° Orbit Inclination)



STK v8.1.3 simulation results, 45° inclination orbit.

10° latitude, -45° longitude surface site.

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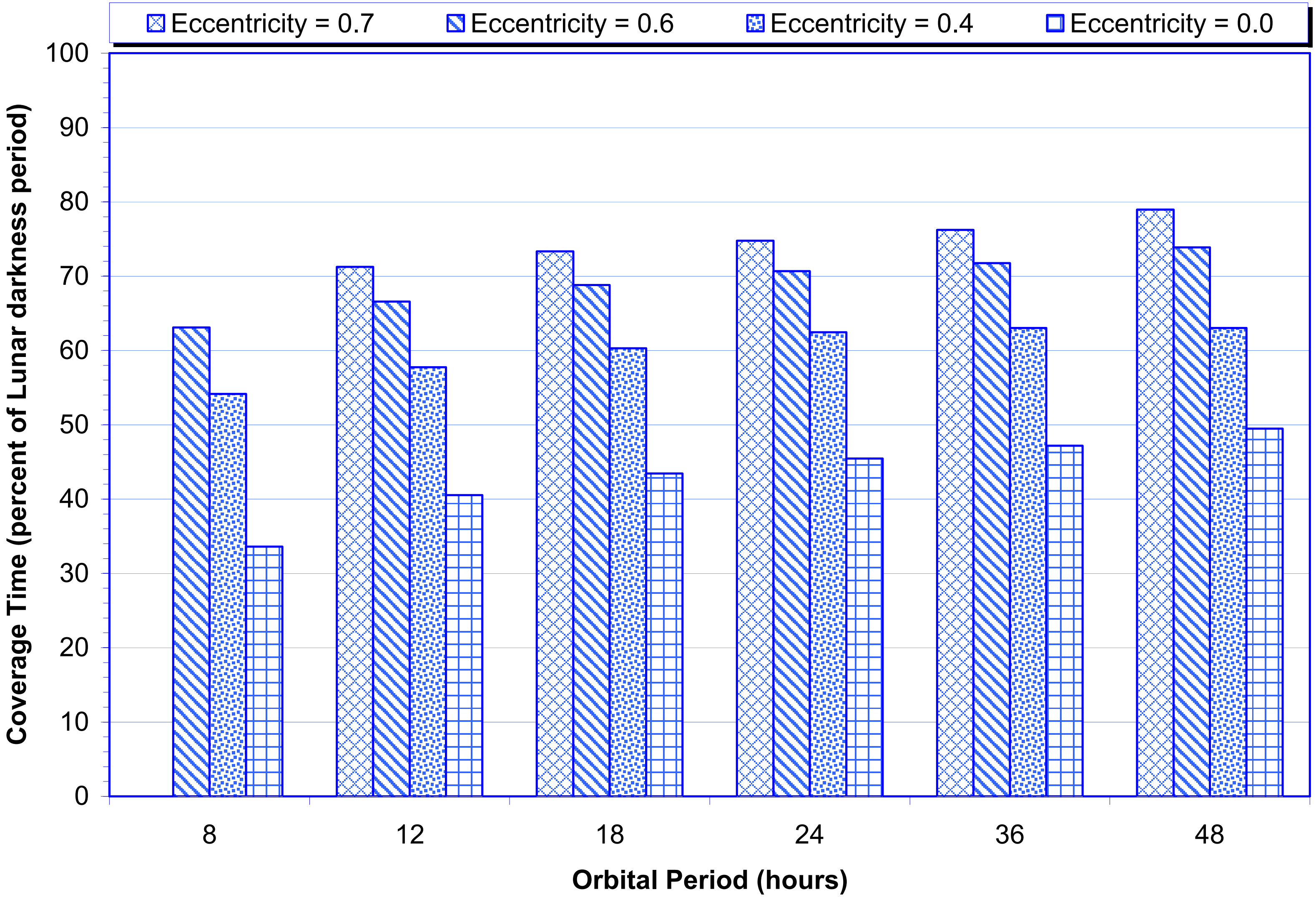
Coverage Summary (Jan 2020, 0° Orbit Inclination)



STK v8.1.3 simulation results.

10° latitude, -45° longitude surface site.

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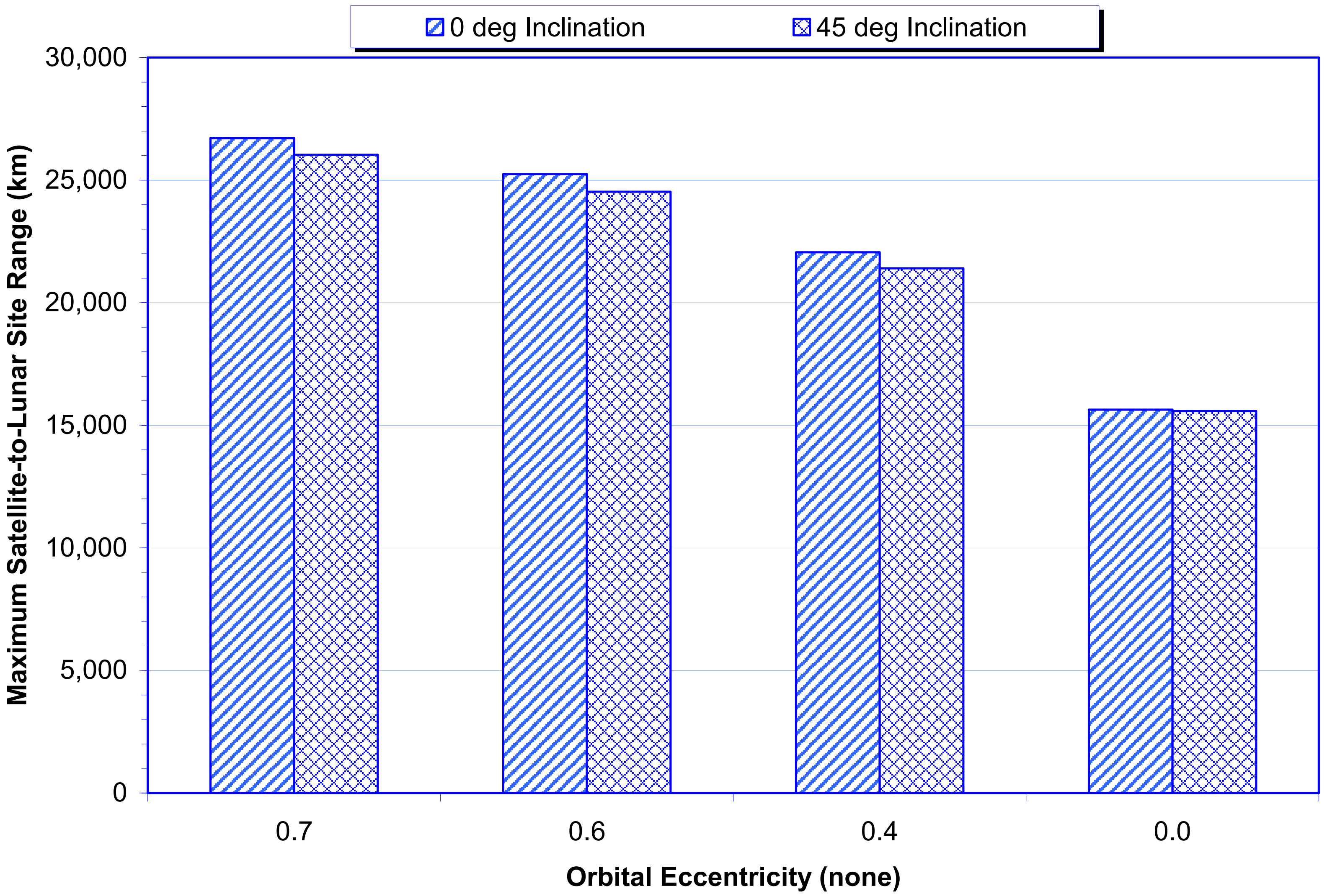
Maximum Range (Jan 2020, 48 hour Orbital Period)



STK v8.1.3 simulation results.

10° latitude, -45° longitude surface site.

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Spacecraft Orbit and Lunar Surface Site Assumptions

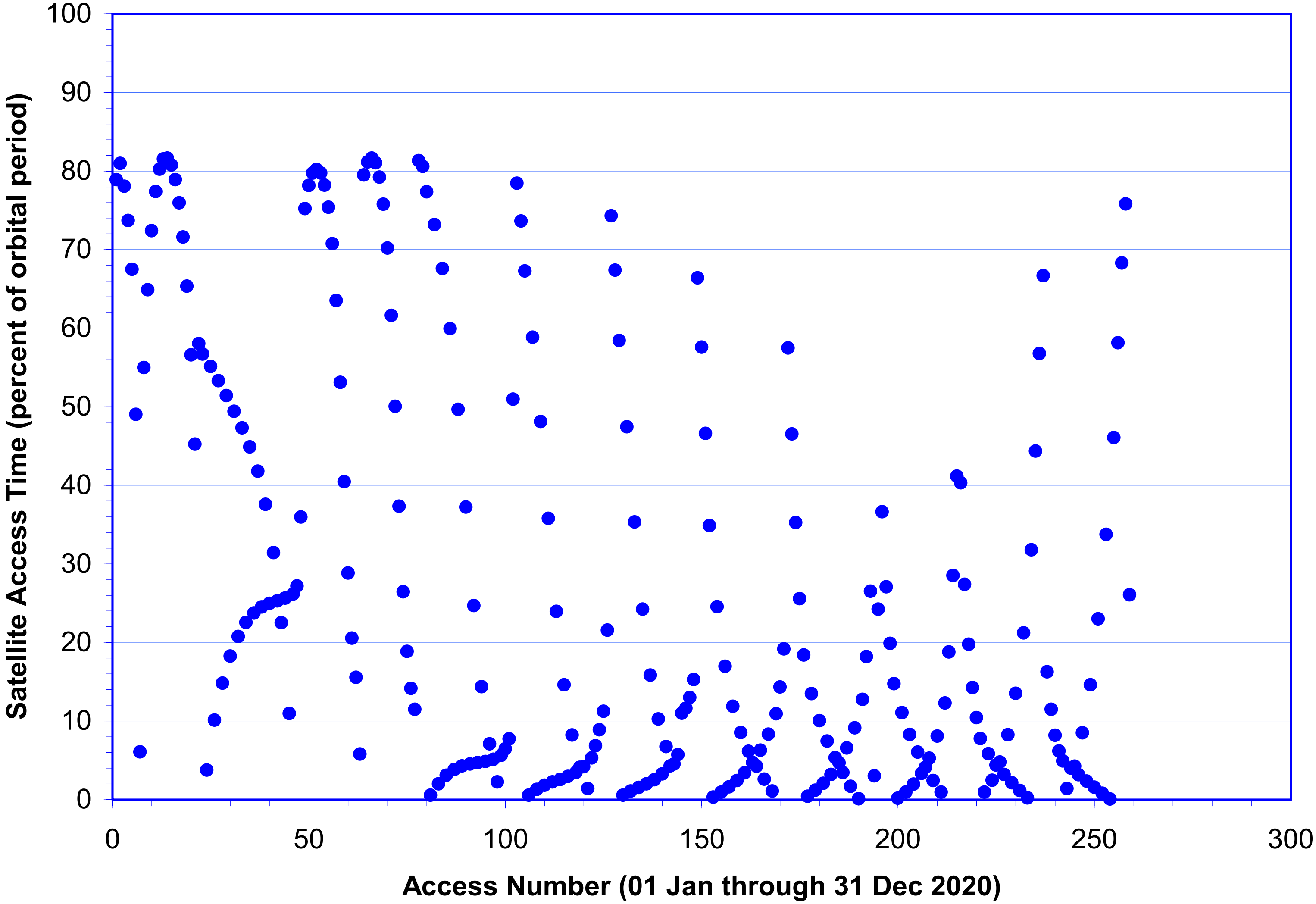
Surface Site

Lat (deg)	Lon (deg)	Alt. (km)
10	-45	0

Satellite

Period (hrs)	SMA (km)	Eccentricity	Inc. (deg)	Arg. (deg)	RAAN (deg)	TA (deg)	Epoch (UTCG)
24	8,049	0.6	45	300	0	120	01 Jan 2020 12:00:00 AM

Access Summary – 24 hour Elliptical Orbit Period



STK v8.1.3 simulation results.

10° latitude, -45° longitude surface site.

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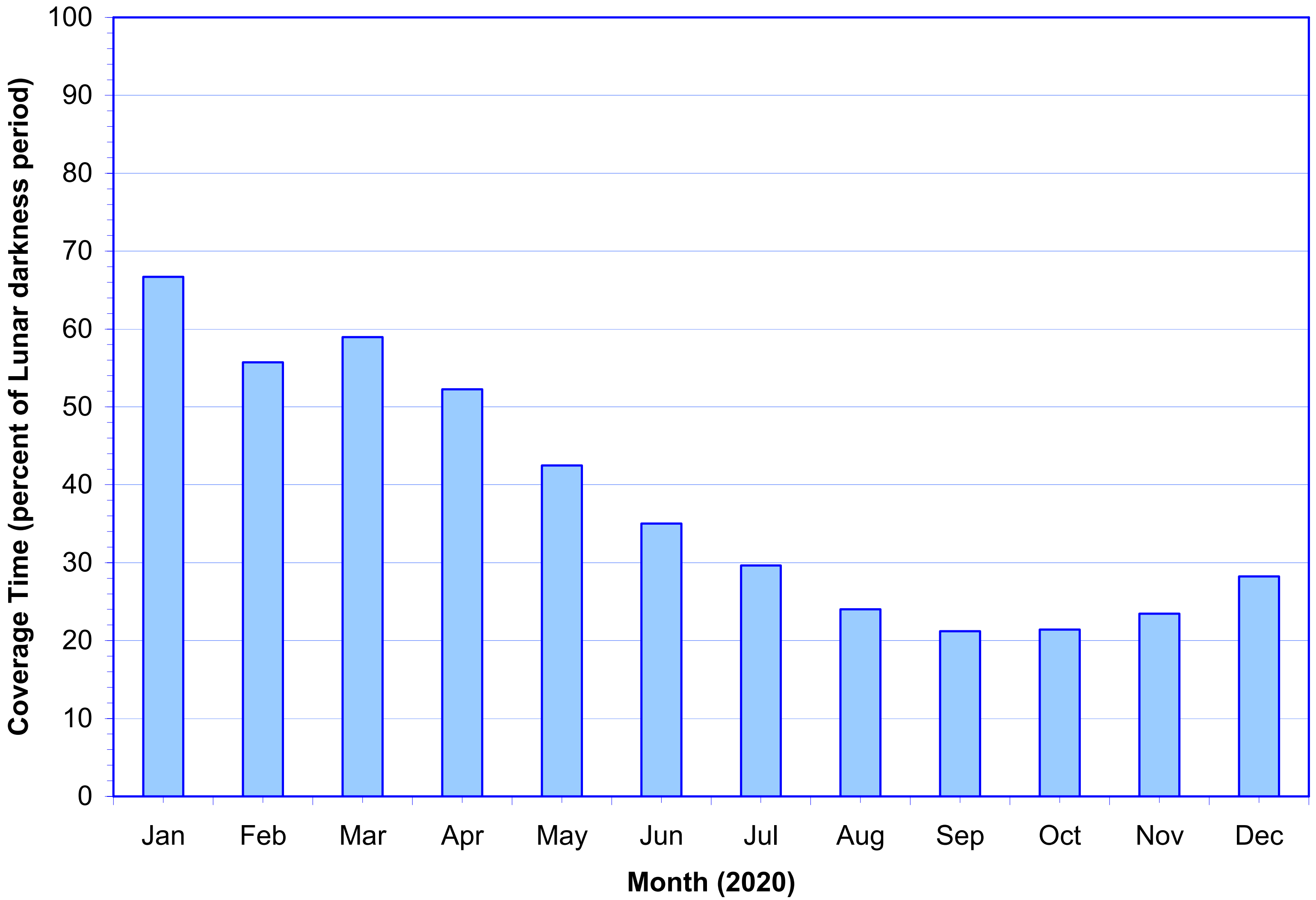
Coverage Summary – 24 hour Elliptical Orbit Period



STK v8.1.3 simulation results.

10° latitude, -45° longitude surface site.

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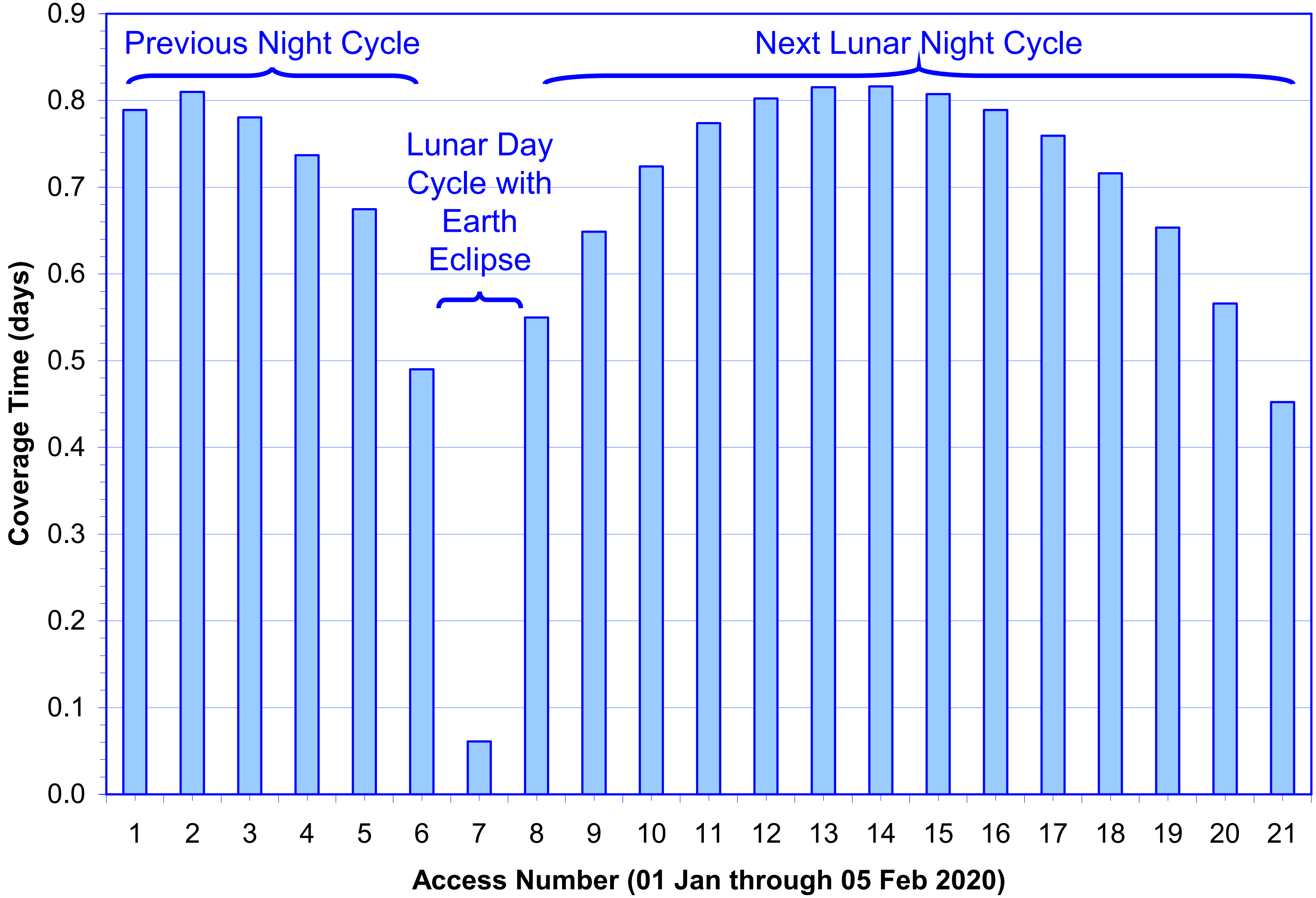
Coverage Details – 24 hour Elliptical Orbit Period



STK v8.1.3 simulation results.

10° latitude, -45° longitude surface site.

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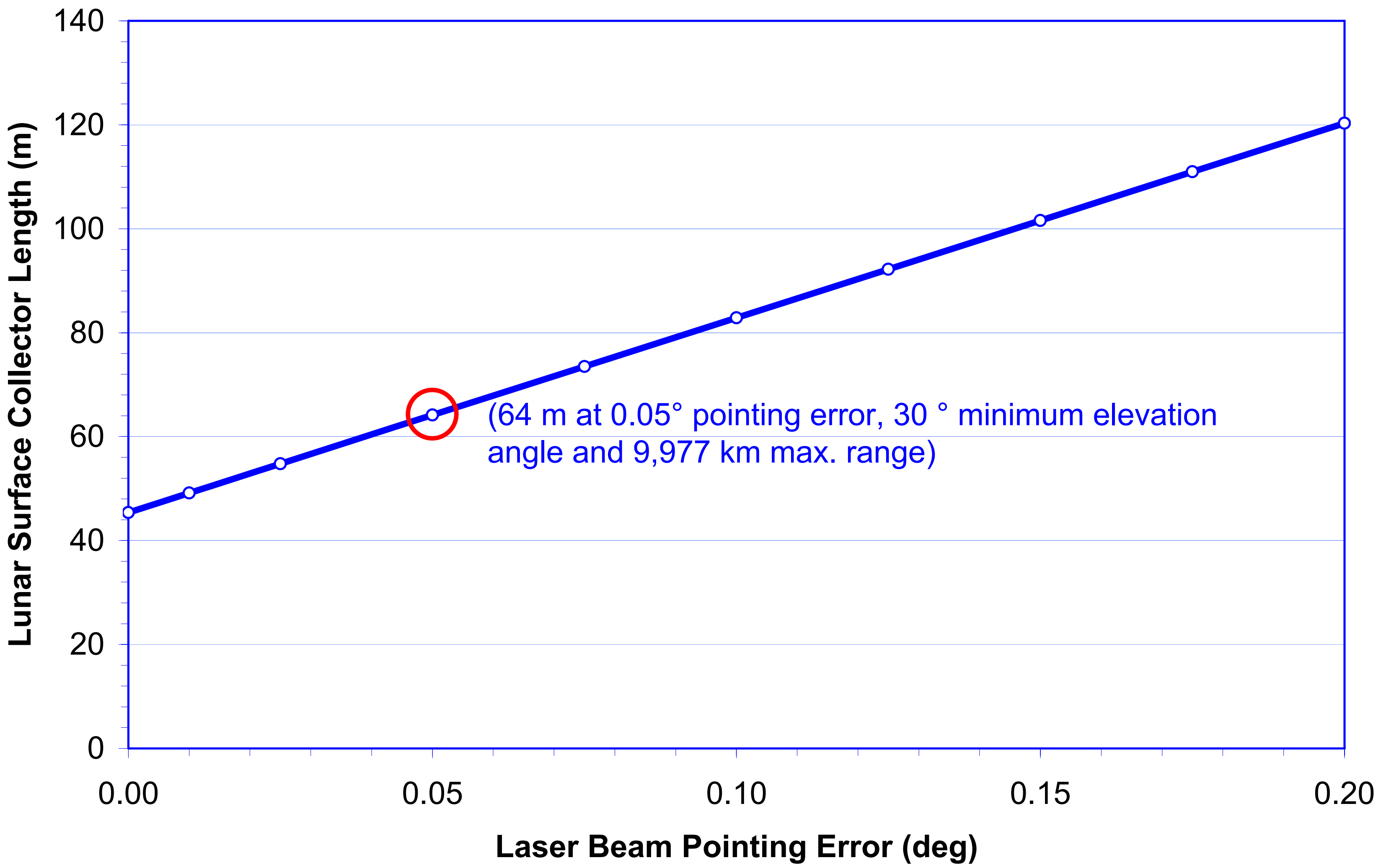
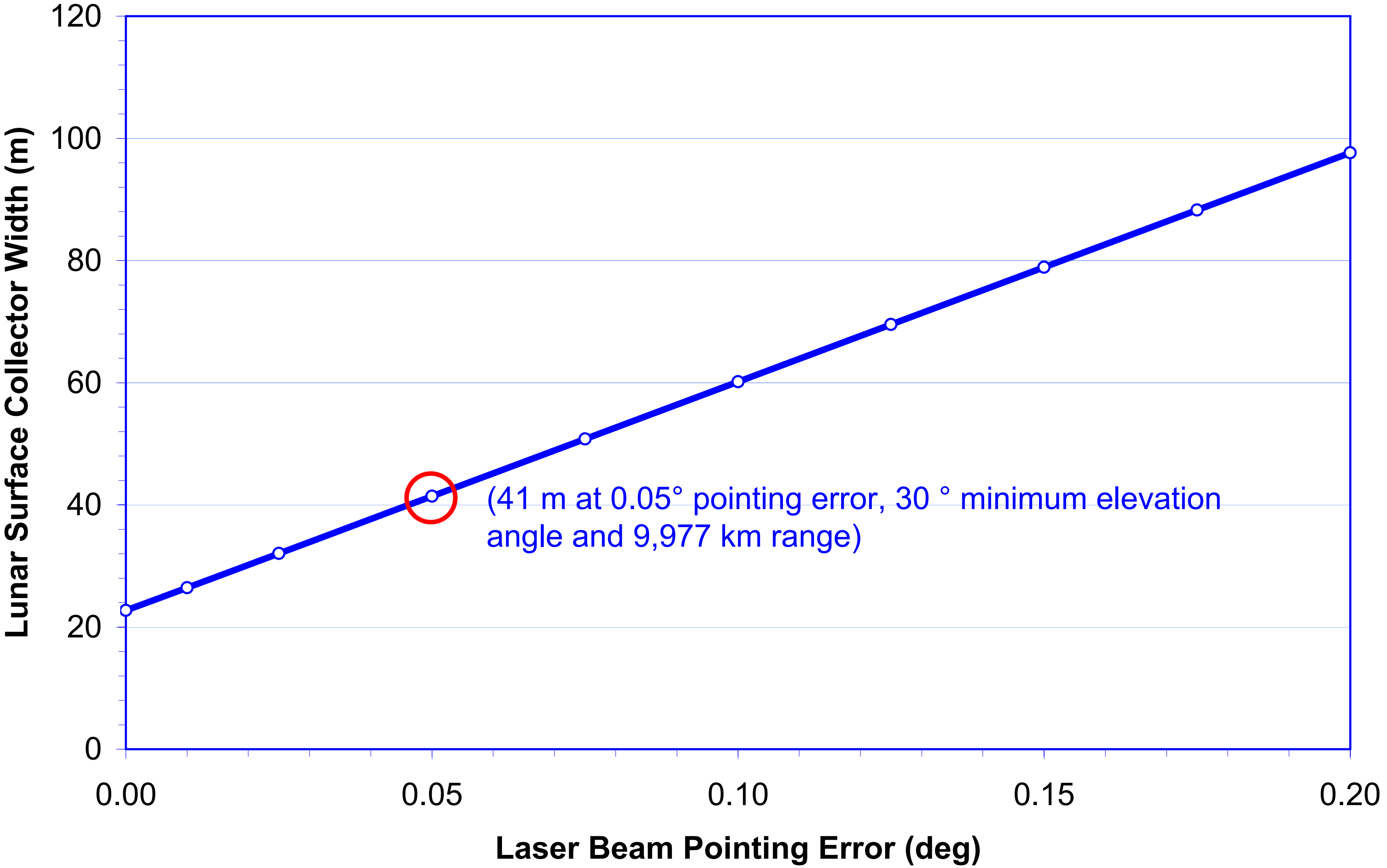
Receiver Length Variation with Pointing Error



Elliptical orbit, 45° inclination, 16.1 hour orbit period. 10° latitude, -45° longitude surface site.

Receiver Width Variation with Pointing Error



Elliptical orbit, 45° inclination, 16.1 hour orbit period.

10° latitude, -45° longitude surface site.

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Surface Receiver Mass and Stowed Volume

Deployed Length	Width	Area	Module Mass	Pwr Cable Mass	Modules	Total Mass
m	m	m^2	kg	kg		kg
24.0	2.5	60	34	1.3	2	71
40.0	2.5	100	54	2.1	2	112
48.0	2.5	120	64	2.5	2	133
54.0	2.5	135	72	2.8	2	149
58.0	2.5	145	77	3.0	2	159
62.0	2.5	155	82	3.2	2	169
64.1	2.5	160	84	3.3	4	350
					Total	1,143

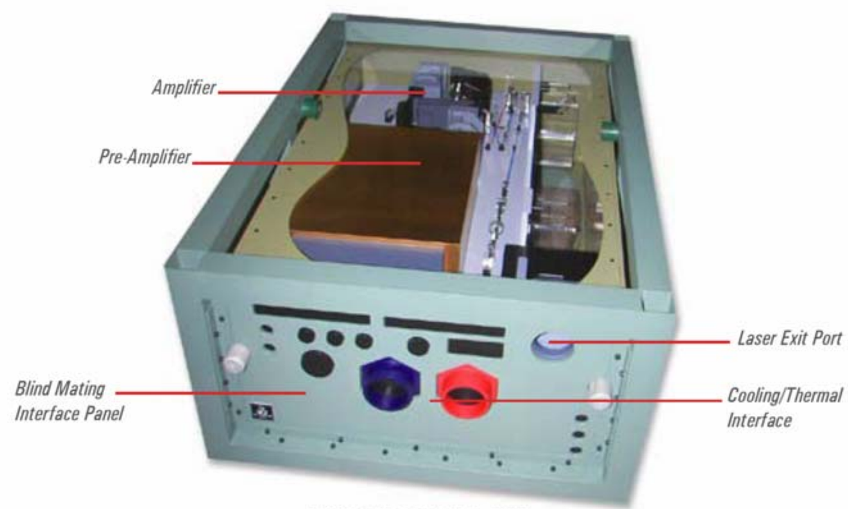
Module mass includes 2 kg for each of two “tent” sections (4 kg total per module).

Deployed Length	Number of Folds	Stowed Length	Stowed Height	Width	Stowed Mod. Vol.	Number of Modules	Total Volume
m		m	m	m	m^3		m^3
24.0	24	1.0	0.057	2.5	0.143	2	0.3
40.0	40	1.0	0.061	2.5	0.153	2	0.3
48.0	48	1.0	0.063	2.5	0.158	2	0.3
54.0	40	1.4	0.061	2.5	0.207	2	0.4
58.0	58	1.0	0.066	2.5	0.164	2	0.3
62.0	62	1.0	0.067	2.5	0.167	2	0.3
64.1	64	1.0	0.067	2.5	0.169	4	0.7
						Total	2.7

Deployed length is for active receiver only, and does not include “tent” section length (3.4 m each end).

1,143 kg and 2.7 m³ surface receiver, 5 kWe power beaming architecture, CIGS PV technology, Jan – Feb 2020.

Northrop-Grumman FIRESTRIKE Laser



15 kW FIRESTRIKE Laser
Line Replaceable Unit (LRU)

FIRESTRIKE™

FEATURES	
Power:	*15kW laser*
Beam Quality:	*Nominally 1.5 times the diffraction limit (vertical beam quality)*
Size:	*Laser head: 12" x 23" x 40" (width, depth, height)* *Current source: 9" x 13" x 30"*
Runtime:	*Continuous, as long as power and coolant are provided*
Instant Turn-on:	*Zero to full power in less than ½ second*
Safety:	*Remote operation, customer interlock access, internal safety sensors*
Control:	*Common Command and Control (C2) systems and Ethernet interfaces*
Low Power Setting:	*Provides nominally 100 watt alignment beam*
Weight:	*400 lbs per LRU*
Ruggedization:	*Hardened LRUs with compact SSL technology engineered for mobility and field toughness*

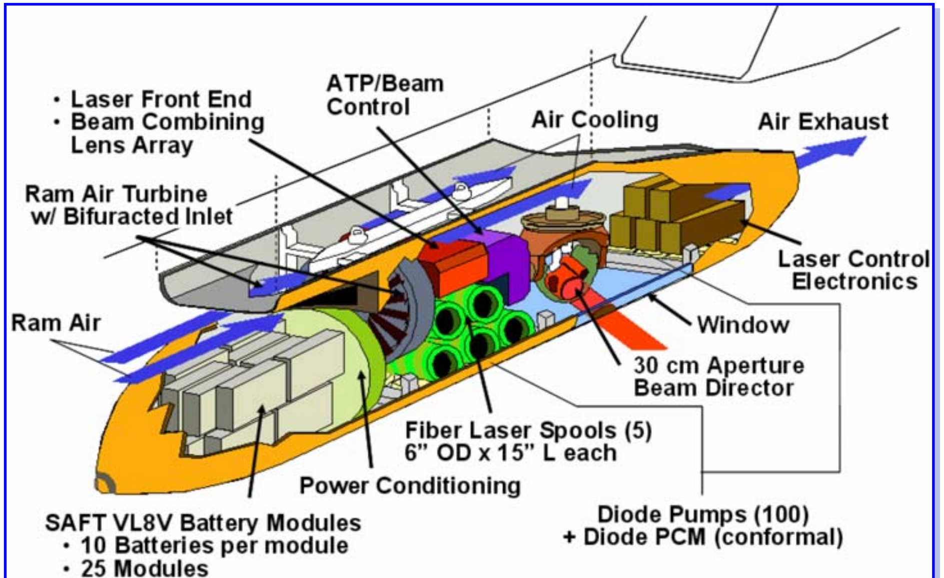
- ***High power, high efficiency laser technology exists***
- ***ONR Lasercomm is emerging***

Two-Axis Ion Thruster Gimbal

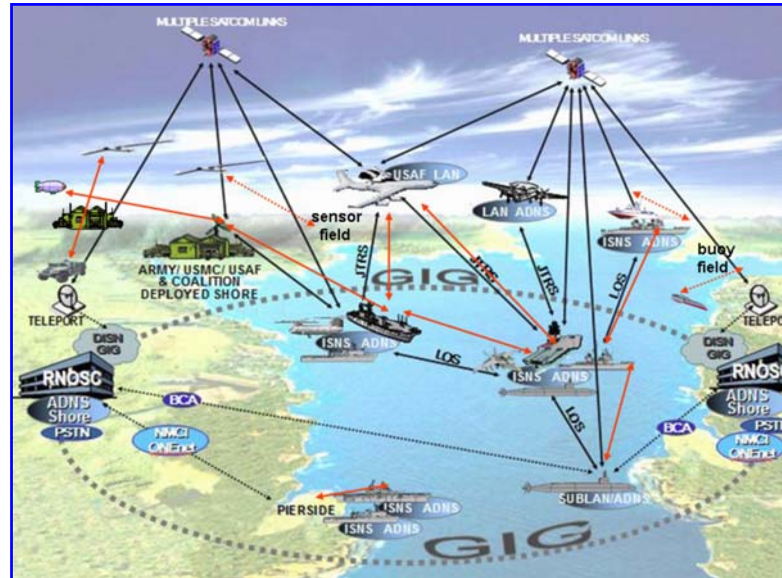
- **Alliance Spacesystems developed two-axis ion thruster gimbal for Dawn asteroid mission**
  - 3.5 kg gimbal supports 7 kg engine
  - Improvement over 17 kg flight-proven Deep Space-1 ion thruster gimbal
  - Two rotary actuators drive composite struts with rod end-bearings mounted in a hexapod configuration
  - Provides two-axis thrust vector pointing

A similar configuration may provide the laser subsystem "rough" pointing function

Office of Naval Research Solid-State Laser



ONR Solid-State Fiber Laser



ONR Lasercomm

Comparison Between Shuttle AFC and Lunar ES Requirement

	Orbiter Alkaline FC	Lunar Energy Storage
Power (kW_e)	12	2 to 5
Duration (hr)	384*	354
Energy (kW-hr)	4,694	2,000

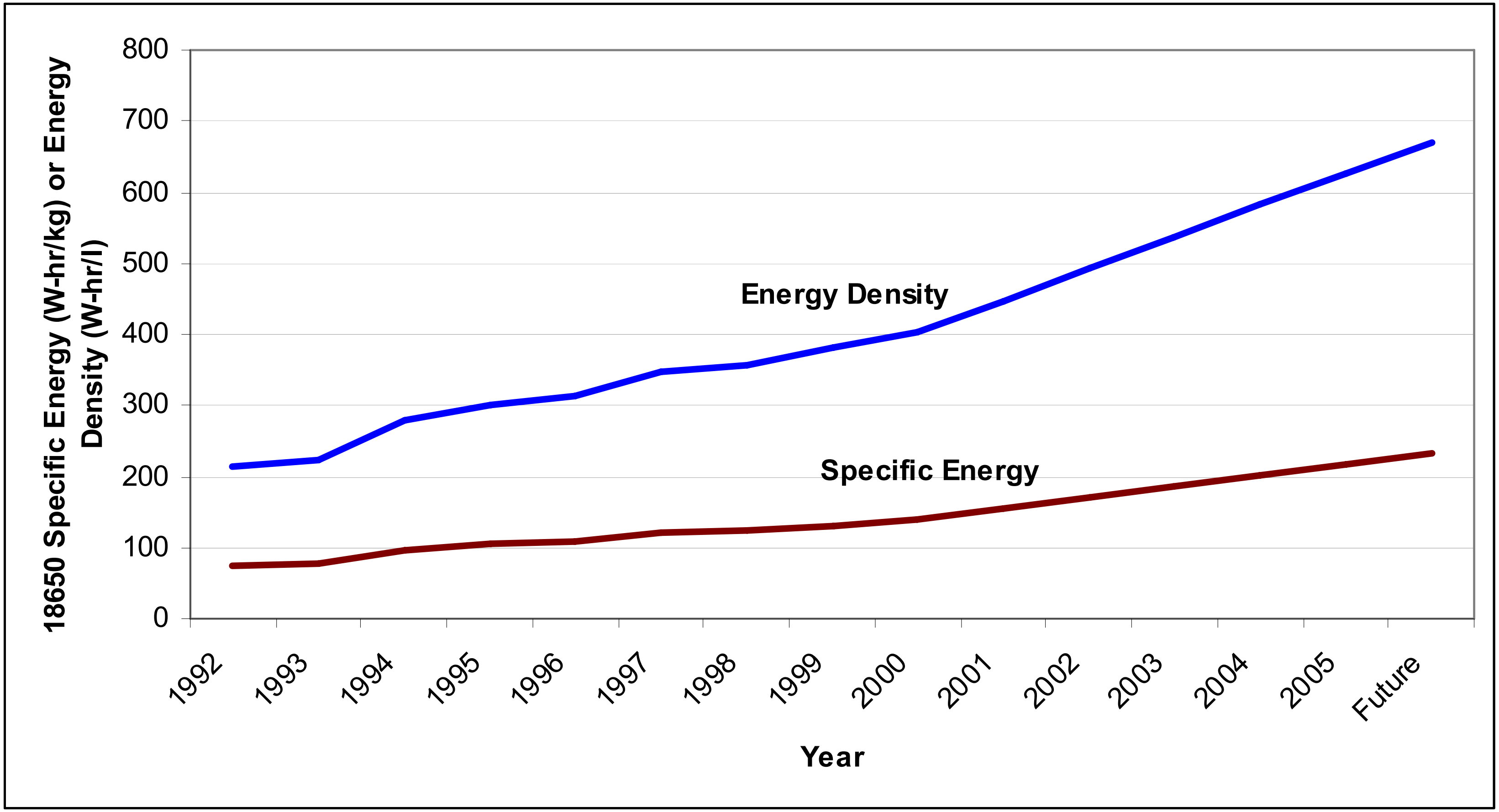
* based on 12 kW, 70% efficiency, 5 cryogenic storage tanks (for Hydrogen and Oxygen), 95.5% Hydrogen usable and 90% Oxygen usable

- **With ~3000 kg mass the Shuttle FC power can provide more than two lunar night cycles (2 months) power needs at 5 kWe**

Li Based Battery Technical Data

Tech.	Type	Voltage (V)	Specific Energy (W-hr/kg)	Energy Density (W-hr/L)	Specific Power (W/kg)	Efficiency (%)	$/E ($/W-hr)	Discharge (%/mo)	Cycles (#)	Life (years)	Application/Comments	Since
Ni	**NiMH**	1.2	30-80	140-300	250-1,000	66%	0.73	20%	1,000		hybrid cars	1983
Li	**Li-Ion (SOTA - Varta)**	3.6	160	270	1,800	99.9%	0.4 - 0.2	5%-10%	1,200	2 to 3	best specific power: 220 W-hr/kg & density: 400 W-hr/l theoretical >0.75kW-hr/kg & >1.8kW-hr/l	1990
	Very H P (VL12V) Li-Ion (SOTA - Saft)	3.6	75	175	5,000 (18 sec at 2.5 V)				300,000 (3% DOD)	15 yrs	-30 to 60 °C (discharge)	2007
	Li-Ion for EV (SOTA - Yardney)		145	358					2,100 (80% DOD)		-40 to 65 °C (discharge)	
	Li-Ion Polymer (SOTA - GRC)	3.7	< 200	300	2,800	99.8%	0.4 - 0.2	5%/month	>1,000 cycles	2 to 3	PMA	1996
	Li-Ion Polymer (SOTA - Danionics)		180 (G3)	350 (G3)					400 (80% DOD)		-20 - 60 °C	2002
	Thin Film Li Sulfur (Sion Power)	2.1	350 (cell) & 260 (pack) 600 (< 2015)	360 600 (< 2015)	1,000				low cycles		theoretical >2.5kW-hr/kg & >2.6kW	1994
	NanoSafe Nano Titanate (Altairnano)	13.8	100		4,000+	87-95%	2.5		20,000	20	increasing effective area; wide temp range (-50 to 75 °C); charge in <10 min.	2007
	LiTE*STAR Thin film Li-Polymer Solid State (Infinite Power Solutions/ORNL)	> 3.6	200 300 (< 2015)	450 900 (< 2015)	6,000				60,000 70,000 (< 2015)		LiPON electrolyte/separator; Li as anode; 15 µm; wide temp range (-20 to 140 °C); credit card size commercially available	2007
	LiVO2 (A)/LiCoO2 (C) (Subaru)			745								
	Li2FePO4F (U. Waterloo)								Long (no cathode volume changes)			
	Utrathin LIB (MIT nano tube anode)		3X									
	Nano electrodes (France)		several X	several X								
	Si nanowires on s.s. Anode (Stanford)		several X									
	Li Nickel Cathode (Tiax - Johnson Control)		40% better									

18650 Cylindrical Li-Ion Battery Cell Capability Improvement



Hamilton Sundstrand
A United Technologies Company

Flywheel Mass Data

65 kW-hr Flywheel (A Pair)	Flywheel (SOTA)
Max. Speed (RPM x 1,000)	65
Efficiency (%)	85
Mass (kg)	
Flywheel Rotor Mass	282
Motor/Generator Mass	4
Shaft Mass	2
Magnetic Bearing Mass	27
Containment Mass	366
Total	**681**
Specific Energy (W-hr/kg)	**95**

- **By 2015, the estimated flywheel specific energy may still be < 150 W-hr/kg**

Super-Capacitor Technical Data

	Company	Technology	Specific Power (W/kg)	Specific Energy (W-hr/kg)	Power Density (W/l)	Energy Density (W-hr/l)	TRL	Others	Specific Surface Area (m2/g)
SOTA	**Maxwell**	Ultracapacitor	15000	up to 6			9	2.7V/cell	
Advanced	**Tartu tech. (Skeleton Nanolab)**	Carbide Derived Carbon	20000	8	25	13	5	high sp. area (400 - 2000 m^2/kg)	400 - 2000
	MIT LEES	Carbon Nanotube		30 - 60			3		
	PowerStor	Carbon Aerogel			10000	10	9 ("AA" size)	2.5V high sp. area (400 - 1000 m^2/kg)	400 - 1000
	Reticle Carbon	Reticle Carbon (solid active carbon)		7500 (theoretical)			2	high sp. area (> 1000 m^2/kg)	> 1000
	EEstor	Battery-Ultracapacitor Hybrid Barium Titanate		280-342			5	high voltage (3500V) low price ($0.04/Wh)	

- **EEStor, of Cedar Park, Texas, employing a ceramic super-capacitor with a barium-titanate insulator to achieve high specific power: 280 W-hr/kg**